

# Mocking Cross-Correlations from the Radio to Optical

Marcelo Alvarez

***Collaborators:***

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# **Motivation: Mocks of LSS Observations**

## **Galaxy Surveys**

e.g. HSC, DES, LSST, Euclid, eROSITA, WFirst

## **CMB**

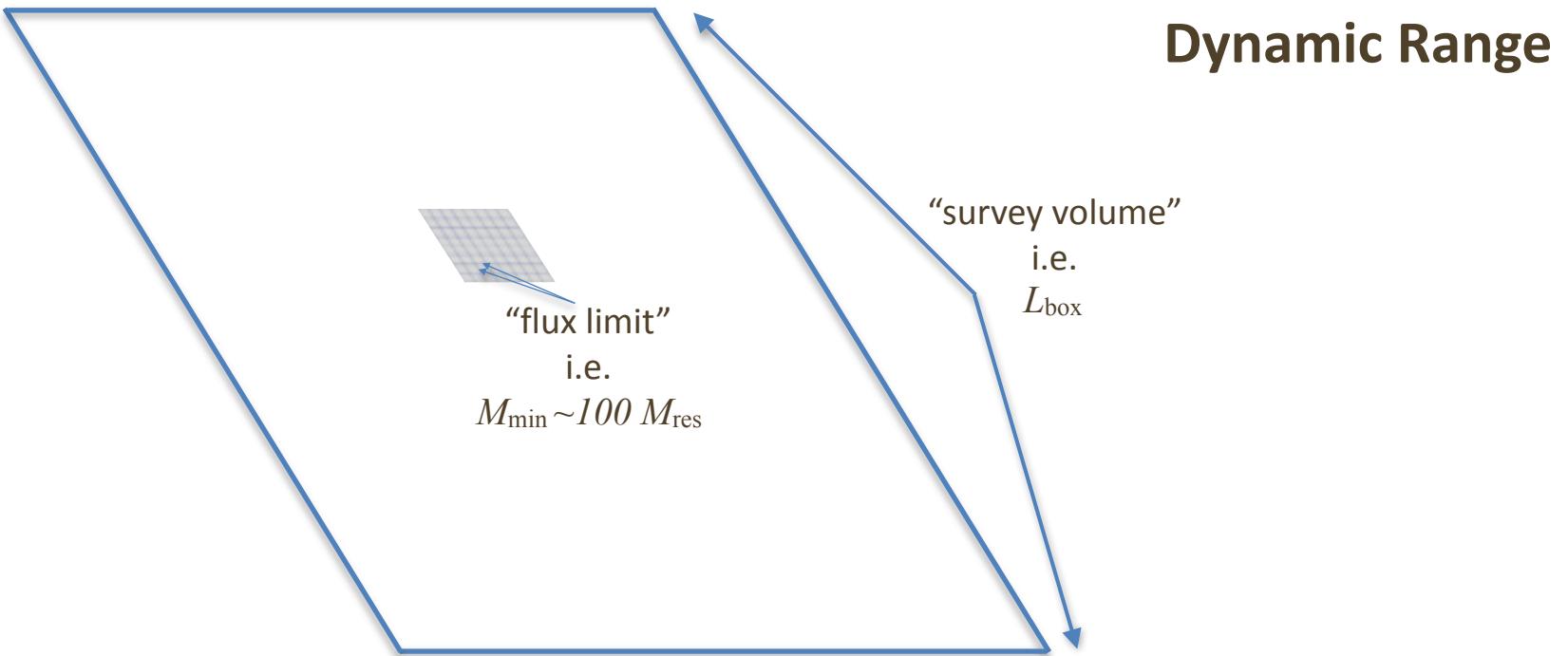
e.g. Planck, Advanced ACTPol, SPT-3G, CMB-S4

## **Intensity Mapping**

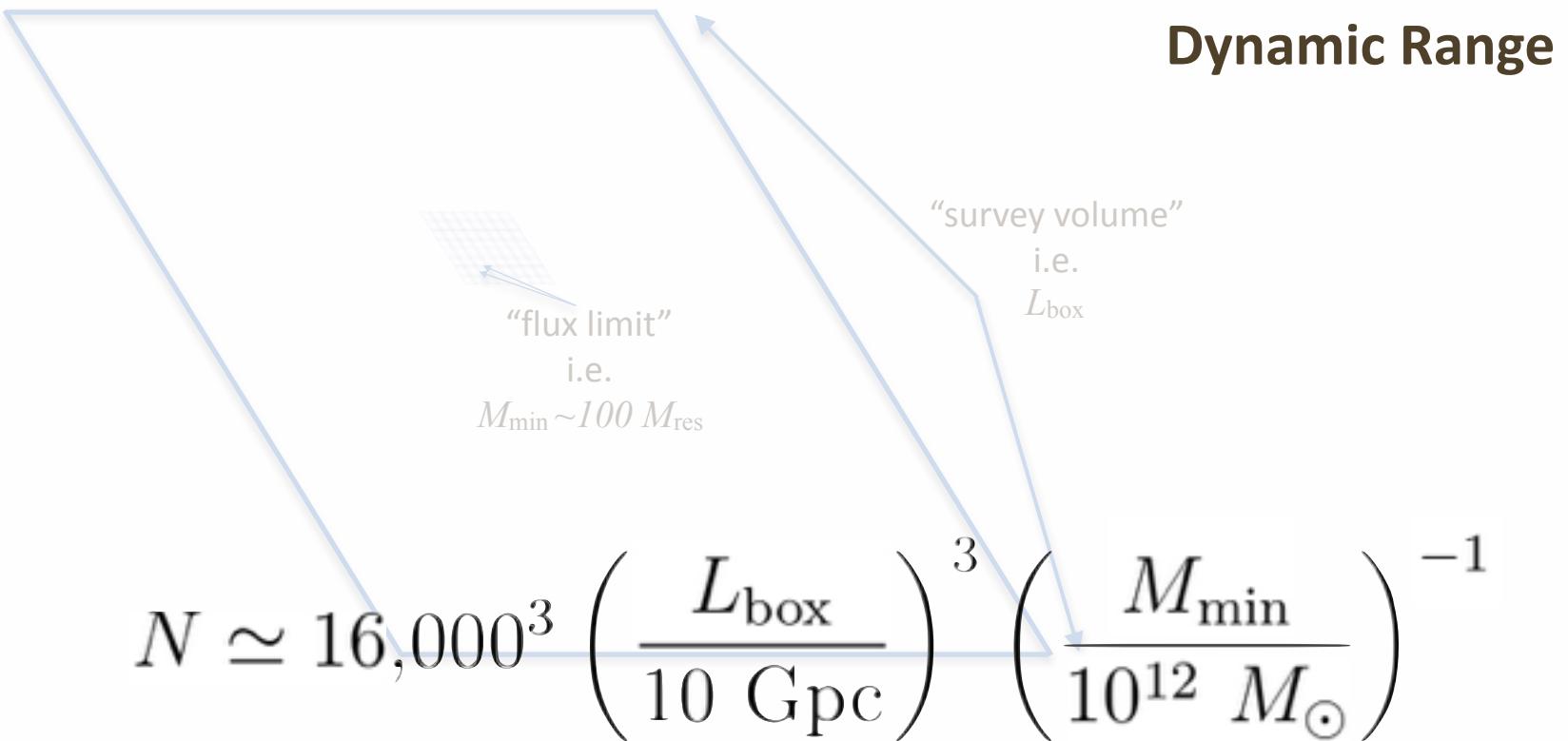
e.g. CHIME, SPHEREx, Tian-Lai, HIRAX, COMA



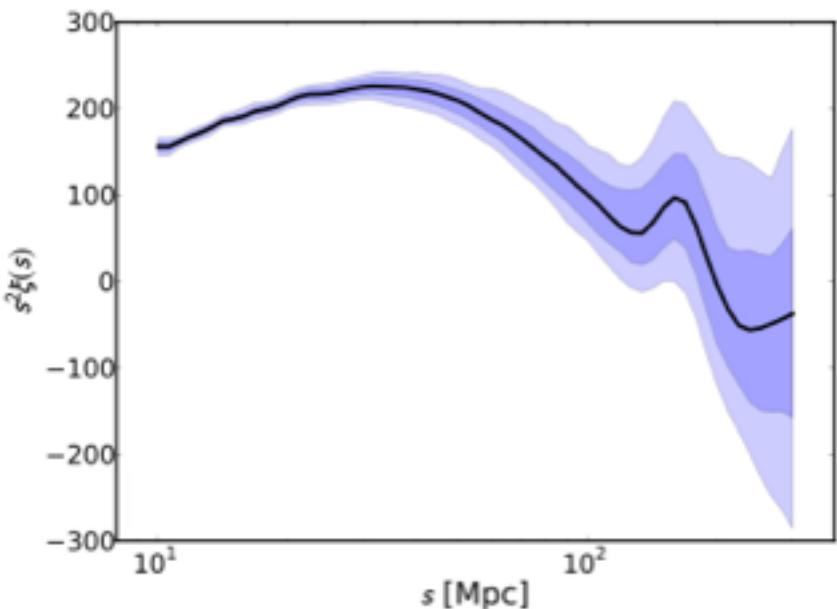
# Mocks of LSS Observations: Key Challenges



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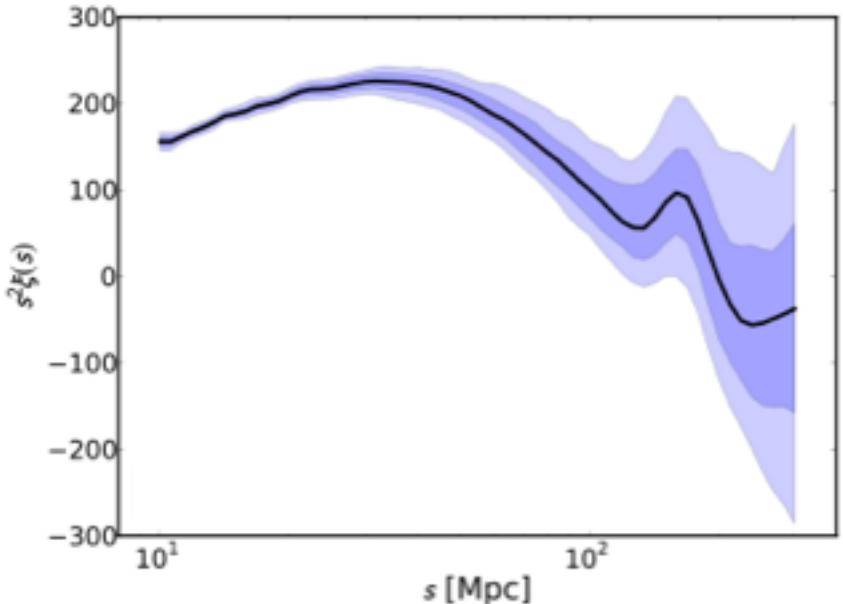
i.e.  
 $M_{\min} \sim 100 M_{\text{res}}$

“survey volume”  
i.e.  
 $L_{\text{box}}$

Speed



# Mocks of LSS Observations: Key Challenges



Speed

“survey volume”  
i.e.  
 $L_{\text{box}}$

i.e.

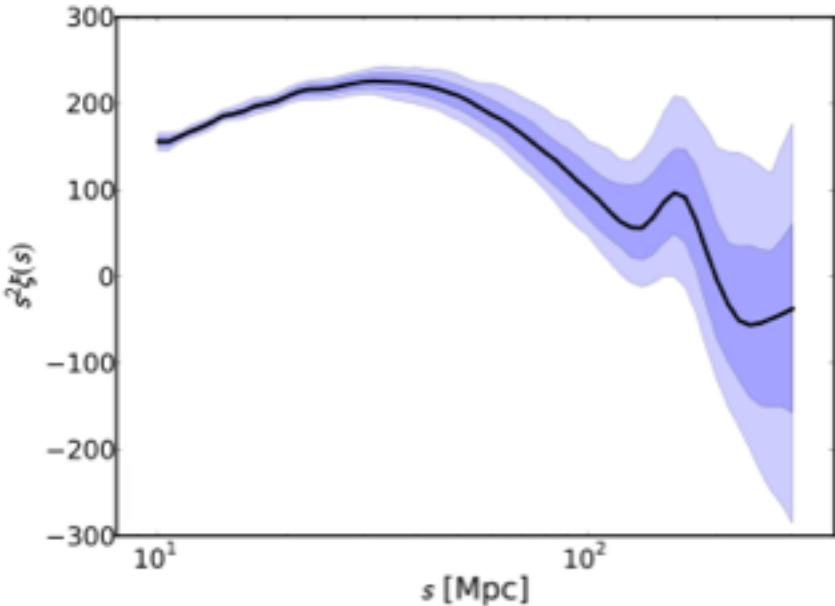
$M_{\Delta} : \sim 100 M_{\odot}$

$$L(\kappa) = P(\Delta|\kappa)$$

$$\propto \det(\mathbf{C}(\kappa))^{-1/2} \exp\left(-\frac{1}{2}\Delta^t \mathbf{C}(\kappa)^{-1} \Delta\right)$$



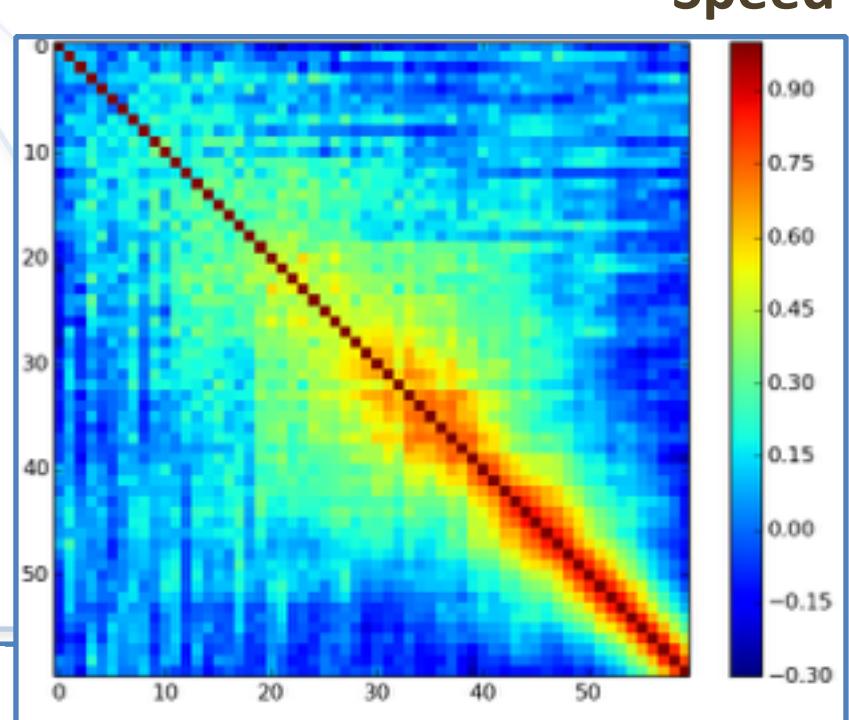
# Mocks of LSS Observations: Key Challenges



i.e.  
 $M_{\min} \sim 100 M_{\text{res}}$

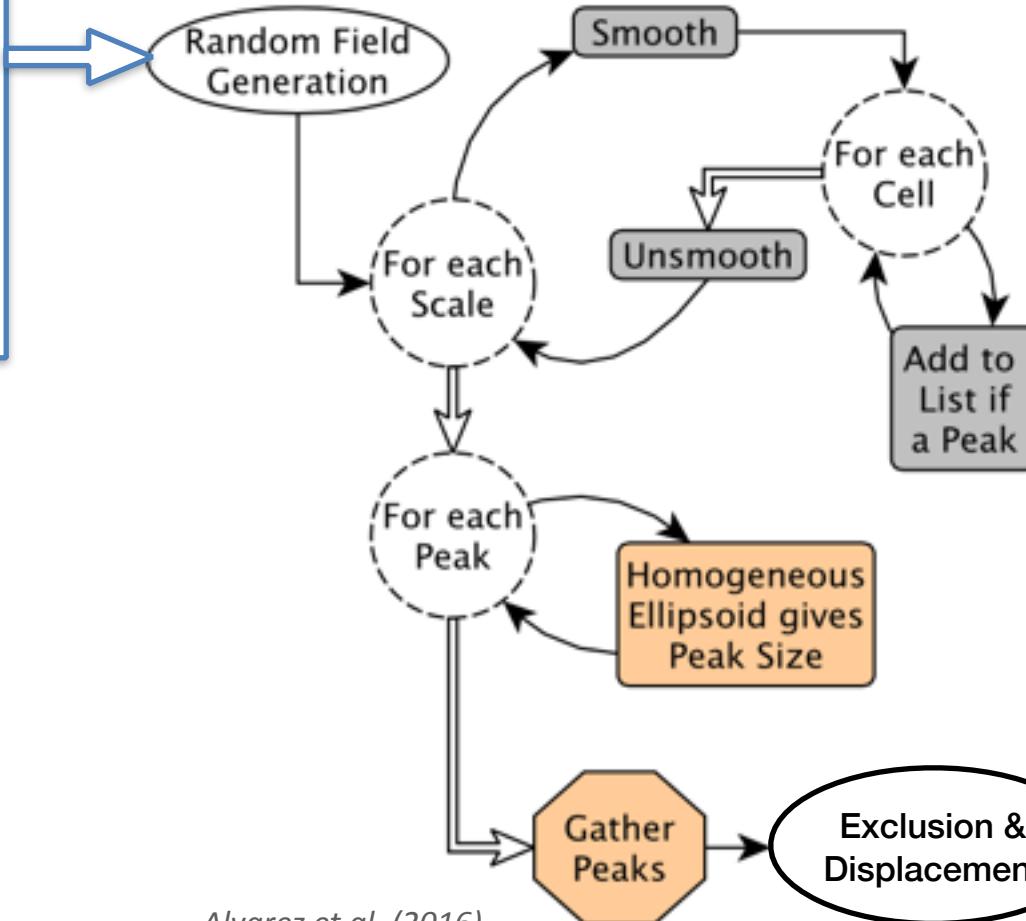
$$L(\kappa) = P(\Delta | \kappa)$$

$$\propto \det(\mathbf{C}(\kappa))^{-1/2} \exp\left(-\frac{1}{2} \Delta^t \mathbf{C}(\kappa)^{-1} \Delta\right)$$



Background  
Cosmology  
+  
Simulation  
Geometry  
+  
Random  
“Seed”

# The Peak Patch Algorithm



Alvarez et al. (2016)

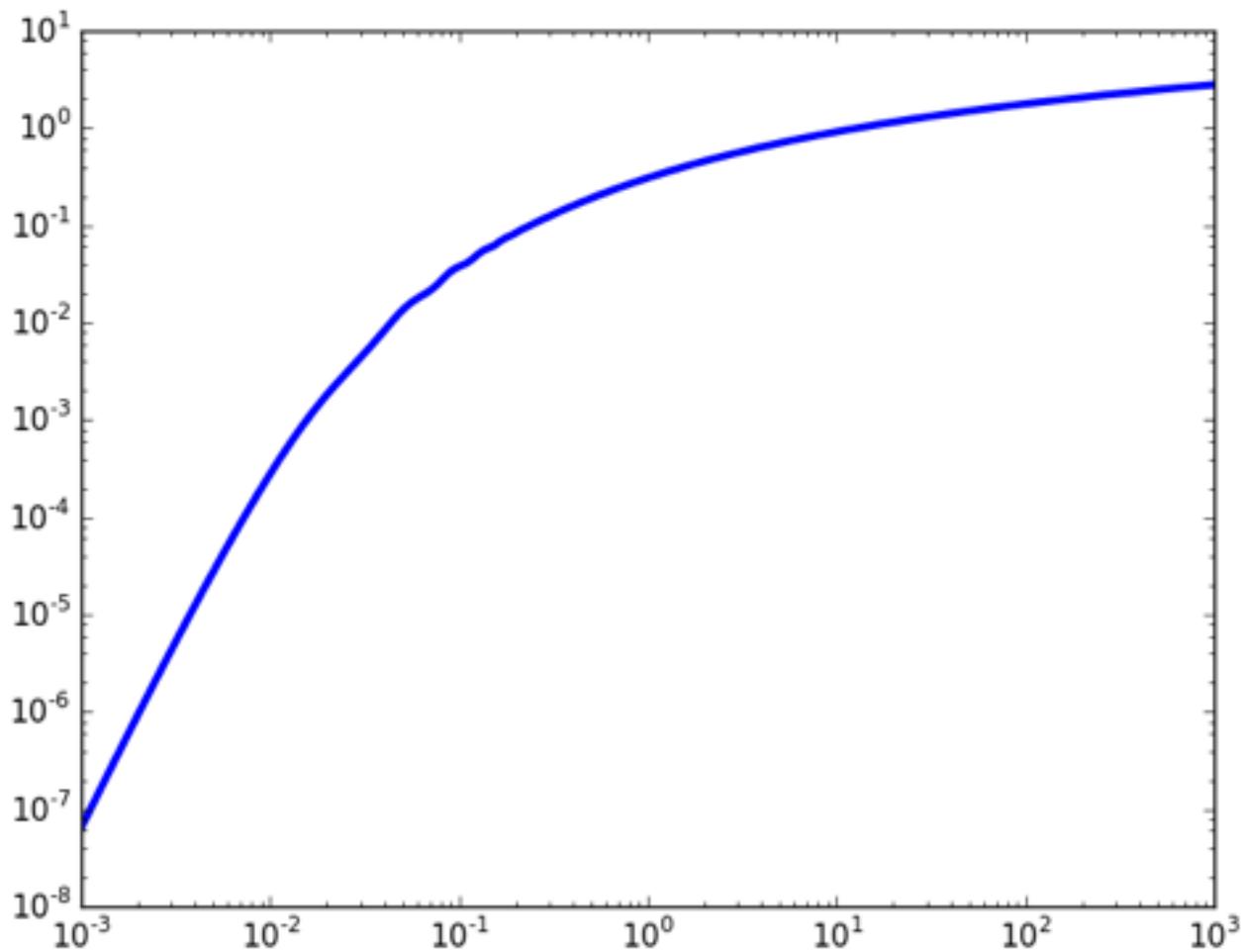
Halo Catalog  
on  
Light Cone  
or  
at Fixed Time



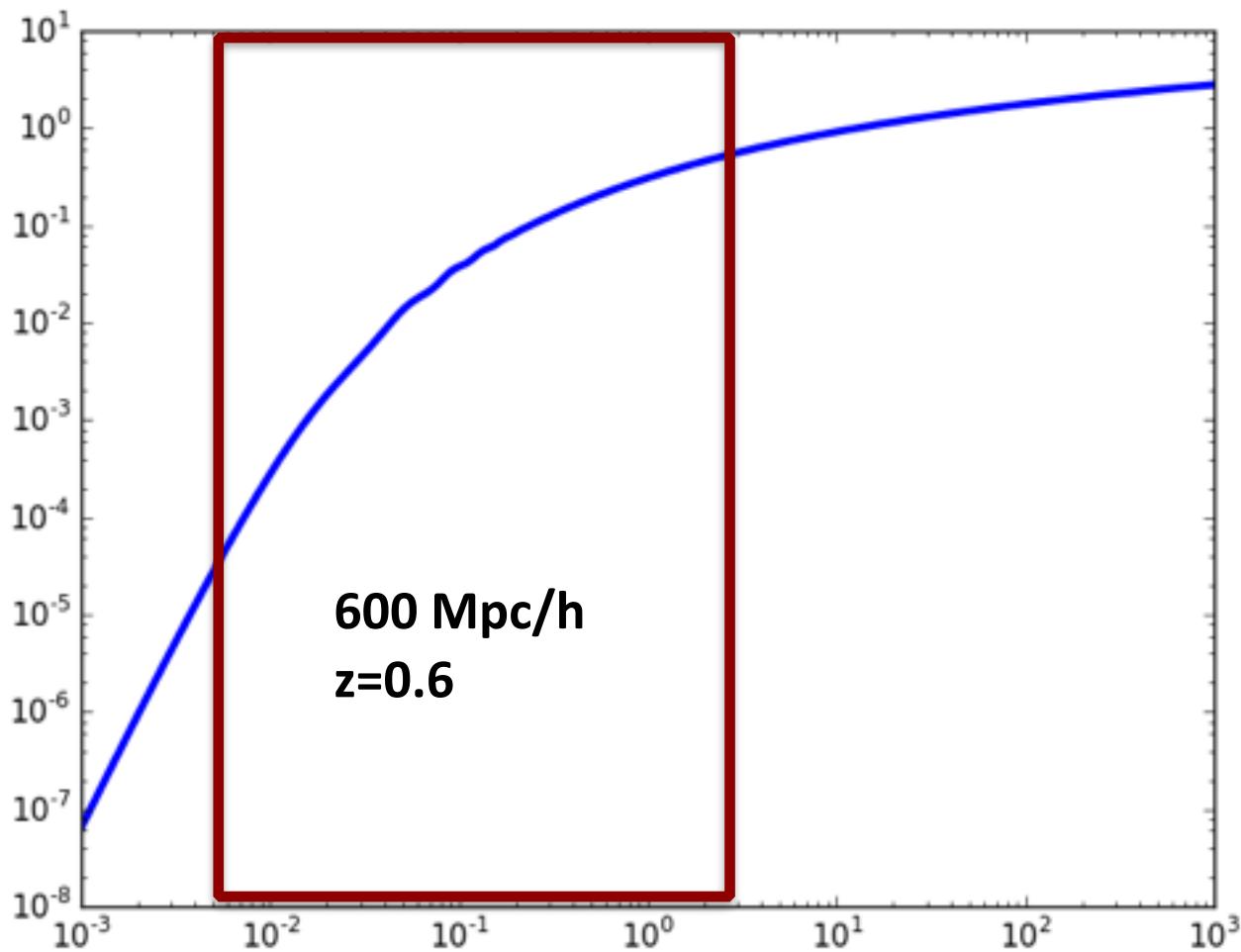
# Validation



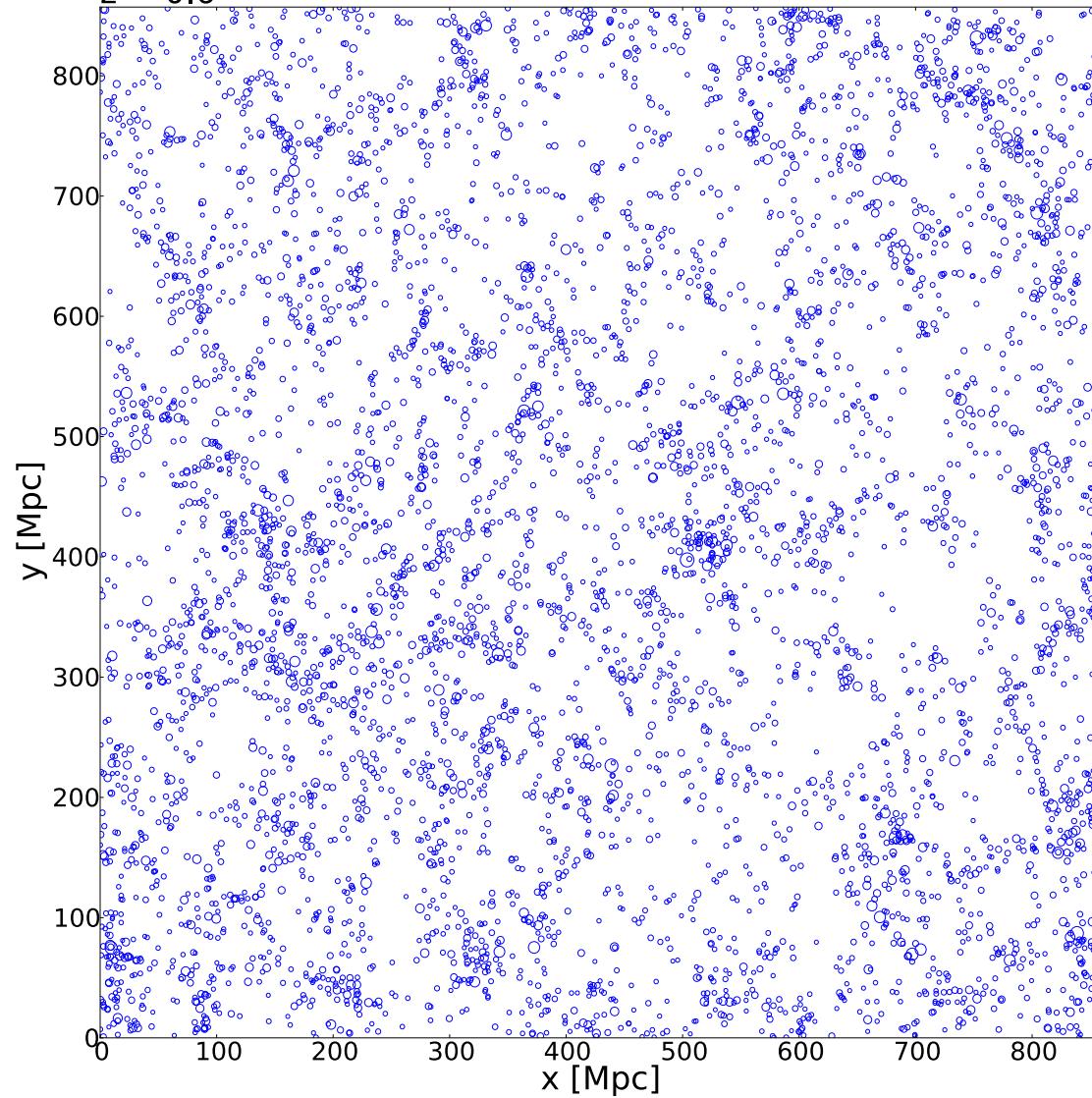
# Scale Dependence of Accuracy: N-body Comparison with same ICs



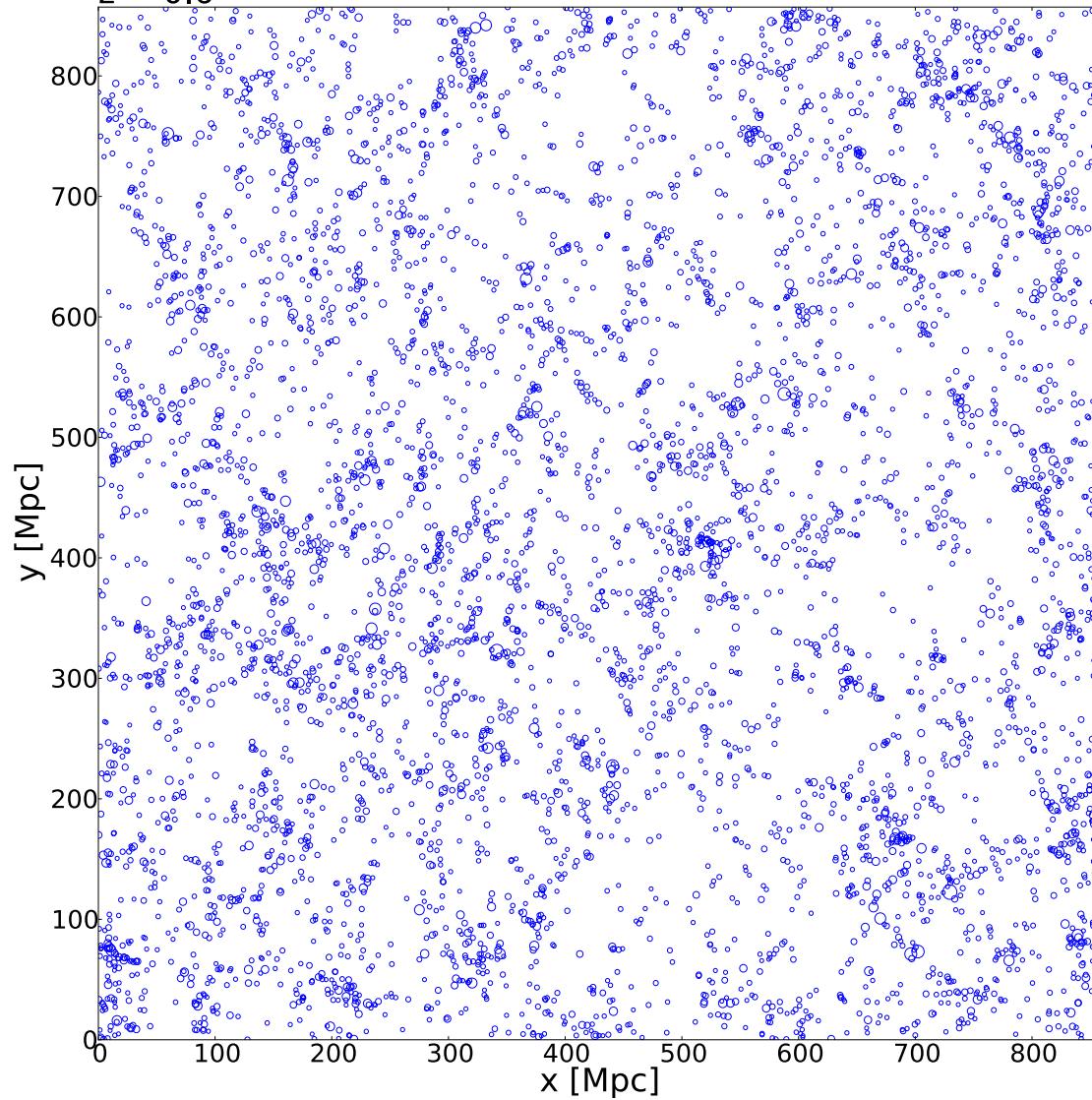
# Scale Dependence of Accuracy: N-body Comparison with same ICs



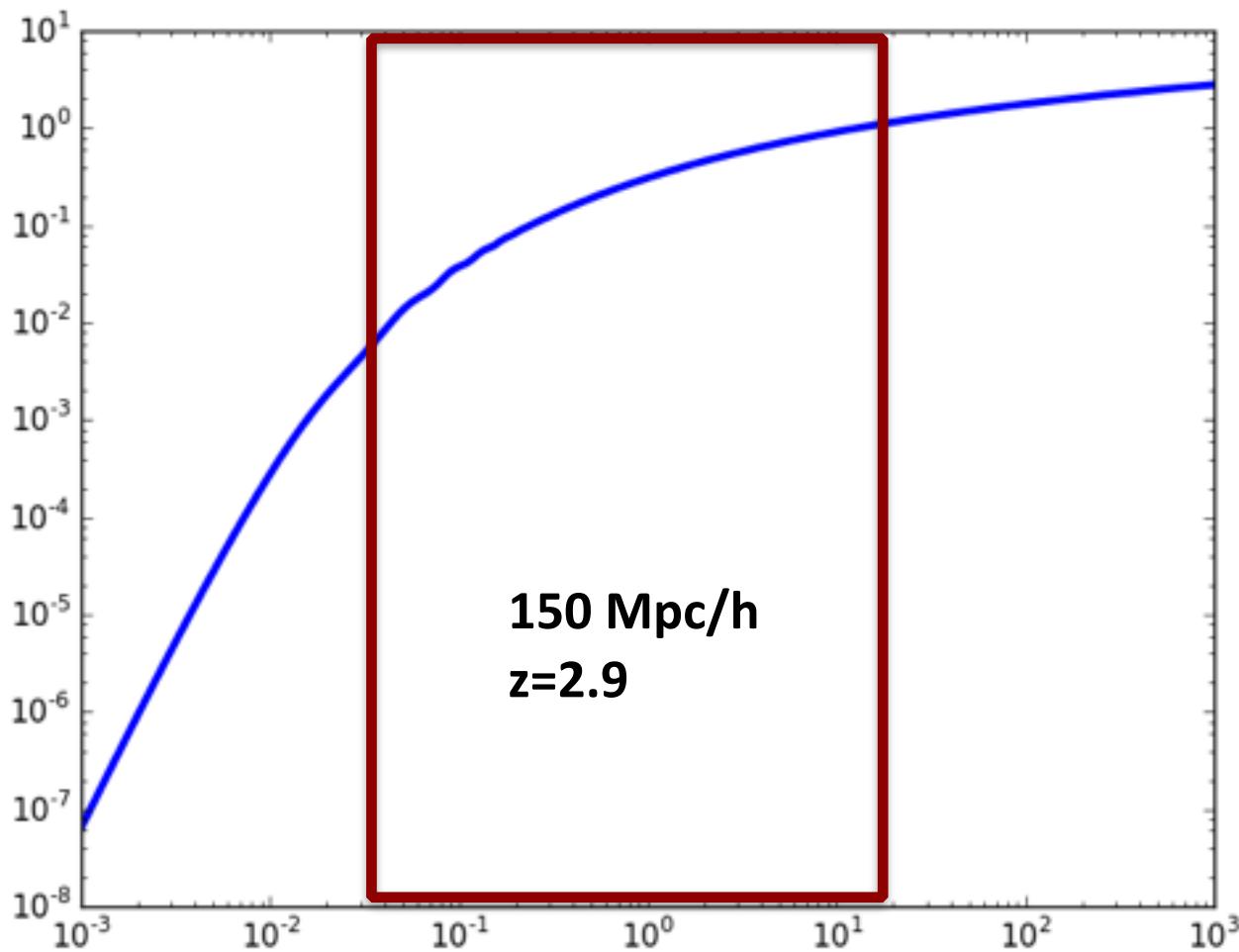
Peak Patch Halos  
600 x 600 x 120 Mpc/h  
 $z = 0.6$



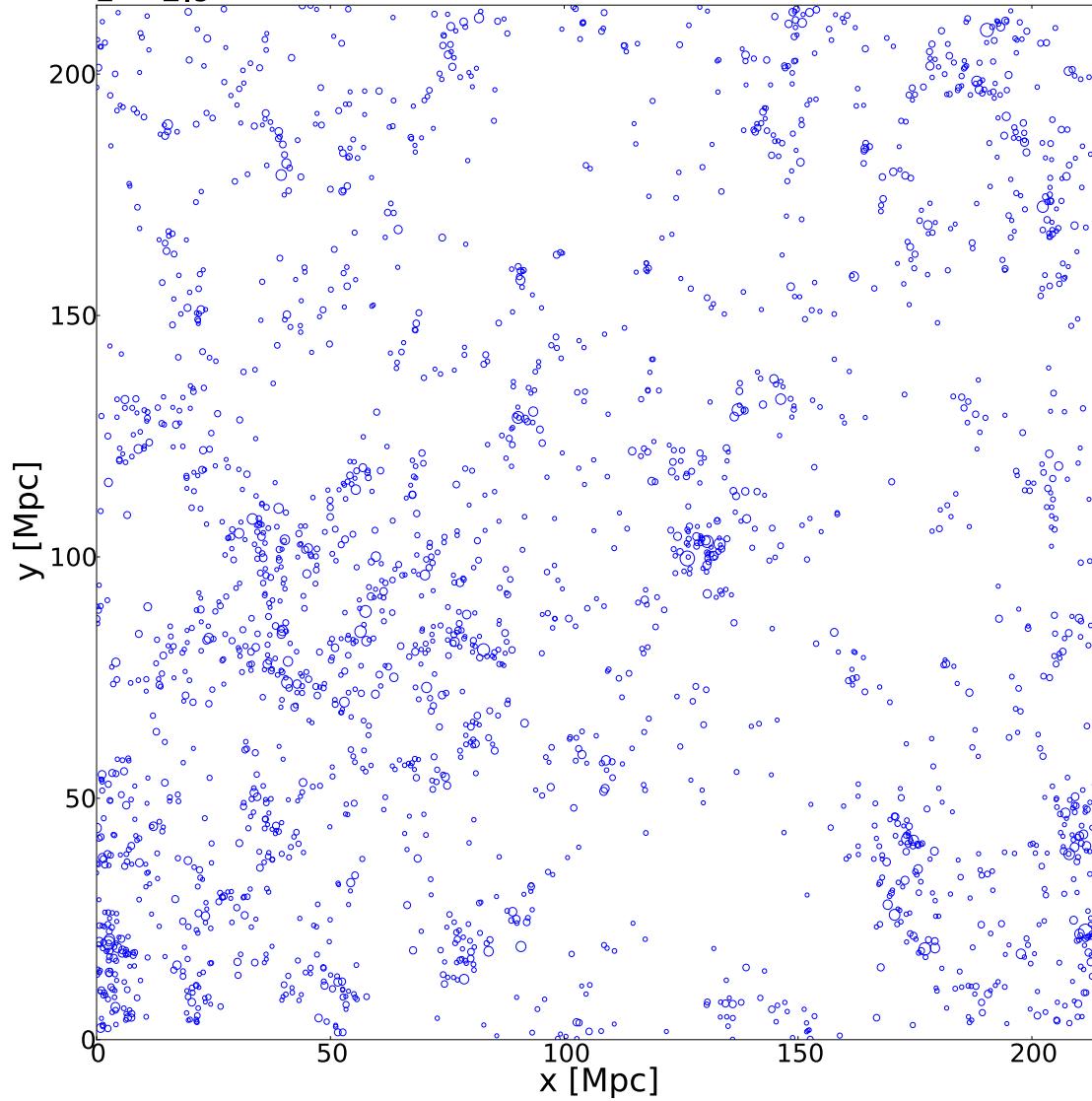
CubeP3M Halos  
600 x 600 x 120 Mpc/h  
 $z = 0.6$



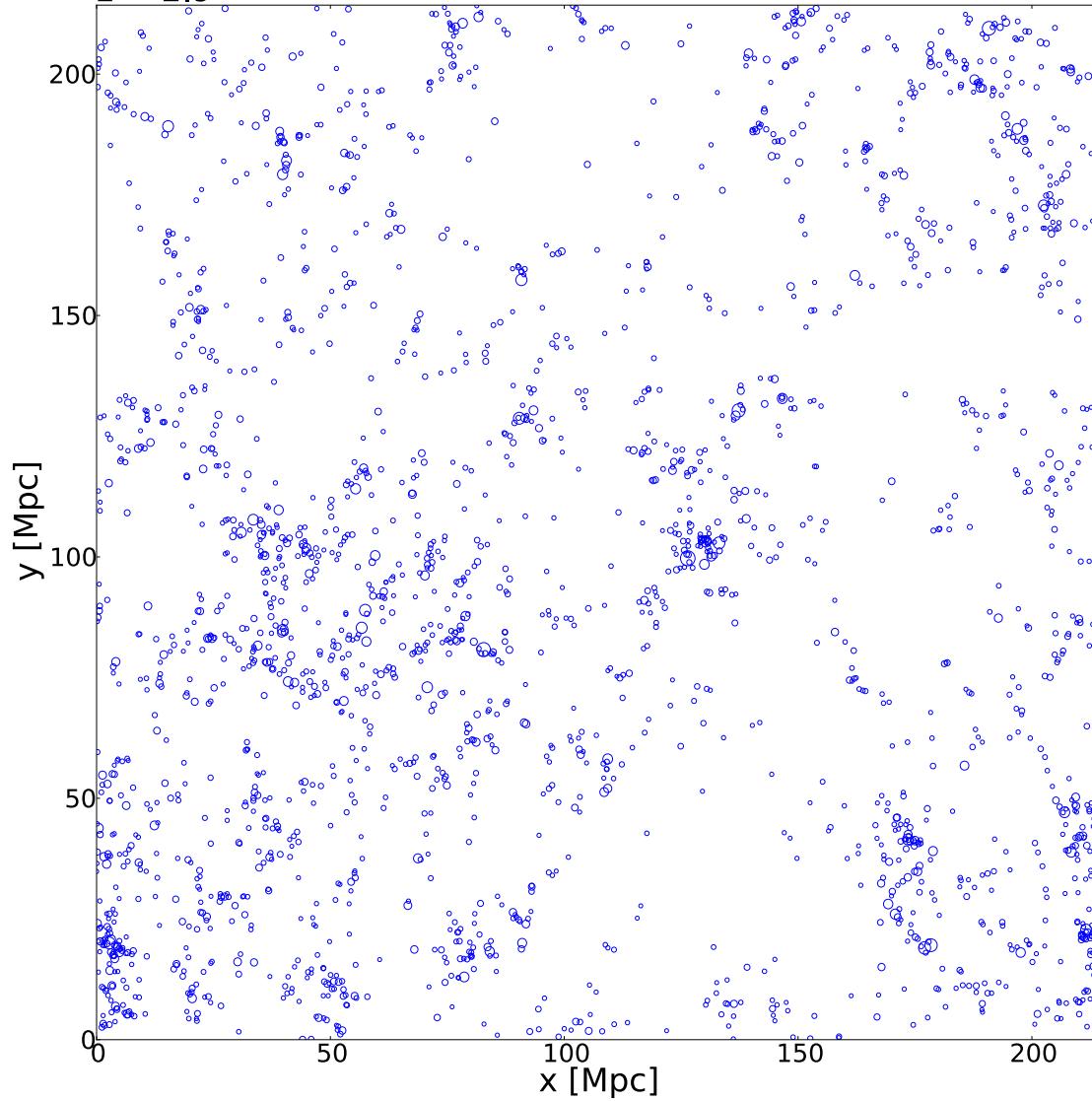
# Dependence on Shape of Power Spectrum



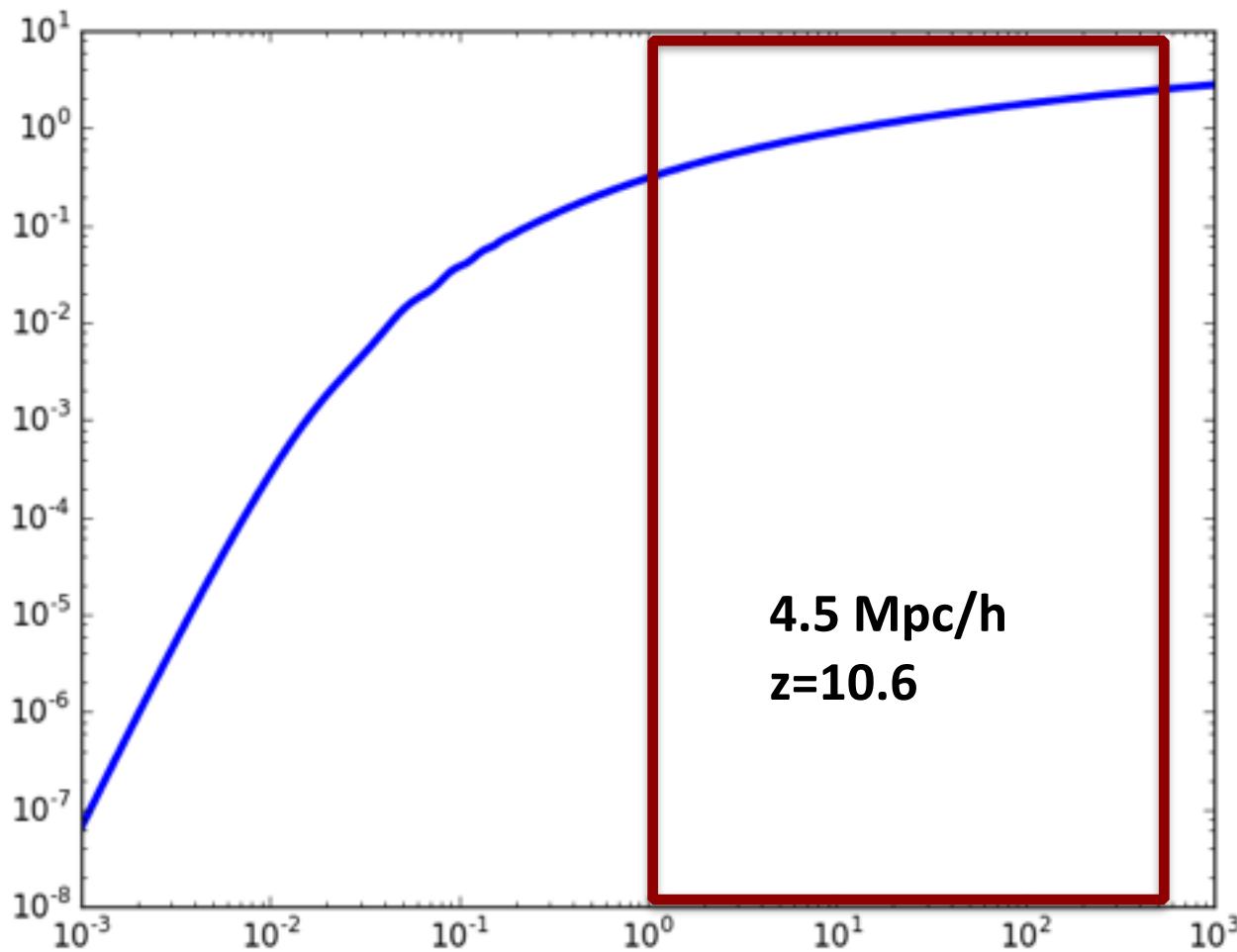
Peak Patch Halos  
150 x 150 x 30 Mpc/h  
 $z = 2.9$



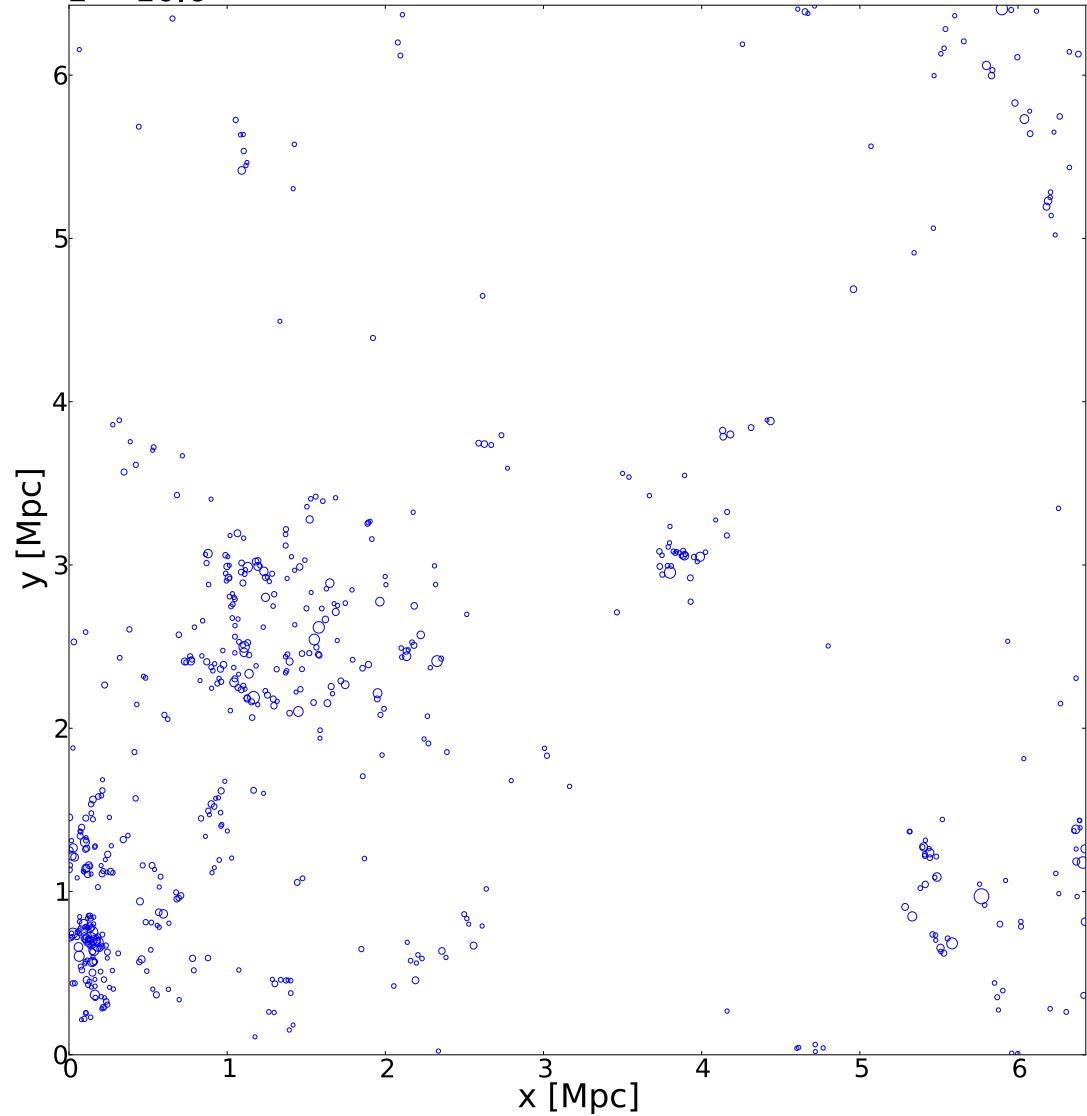
CubeP3M Halos  
150 x 150 x 30 Mpc/h  
 $z = 2.9$



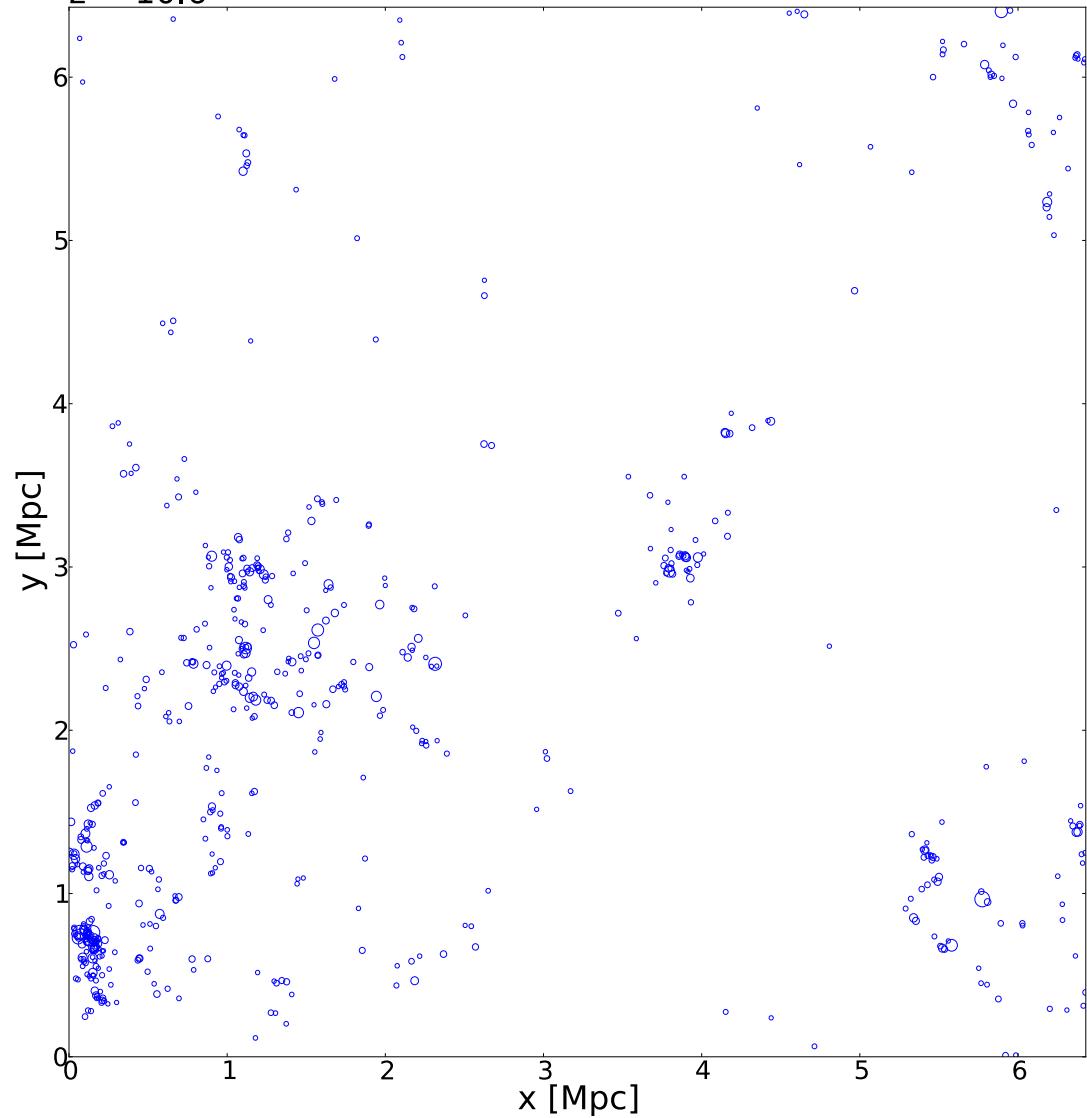
# Dependence on Shape of Power Spectrum



Peak Patch Halos  
 $4.5 \times 4.5 \times 0.9 \text{ Mpc}/h$   
 $z = 10.6$



CubeP3M Halos  
 $4.5 \times 4.5 \times 0.9$  Mpc/h  
 $z = 10.6$



# Applications



# Leveraging Speed & Efficiency of Method: Halo Clustering Statistics

Gpc box –  $1024^3$  cells

Wall clock ~ **3 mins** each on **64 cores**

**z=0** with ~  **$10^6$  halos**

Complete for  $M_{\text{halo}} > 3 \times 10^{12} M_{\text{sun}}$

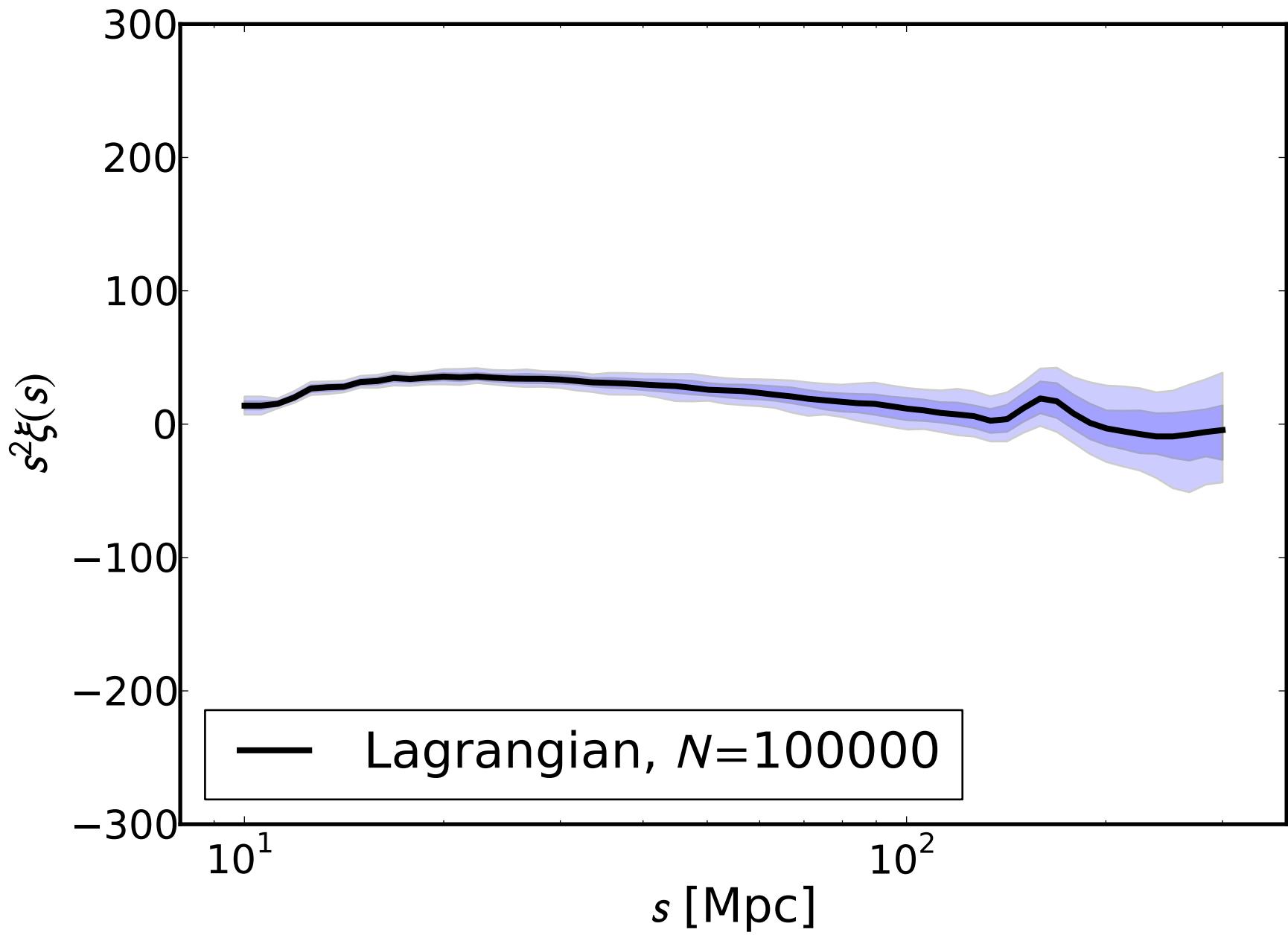
~ **400 realizations**

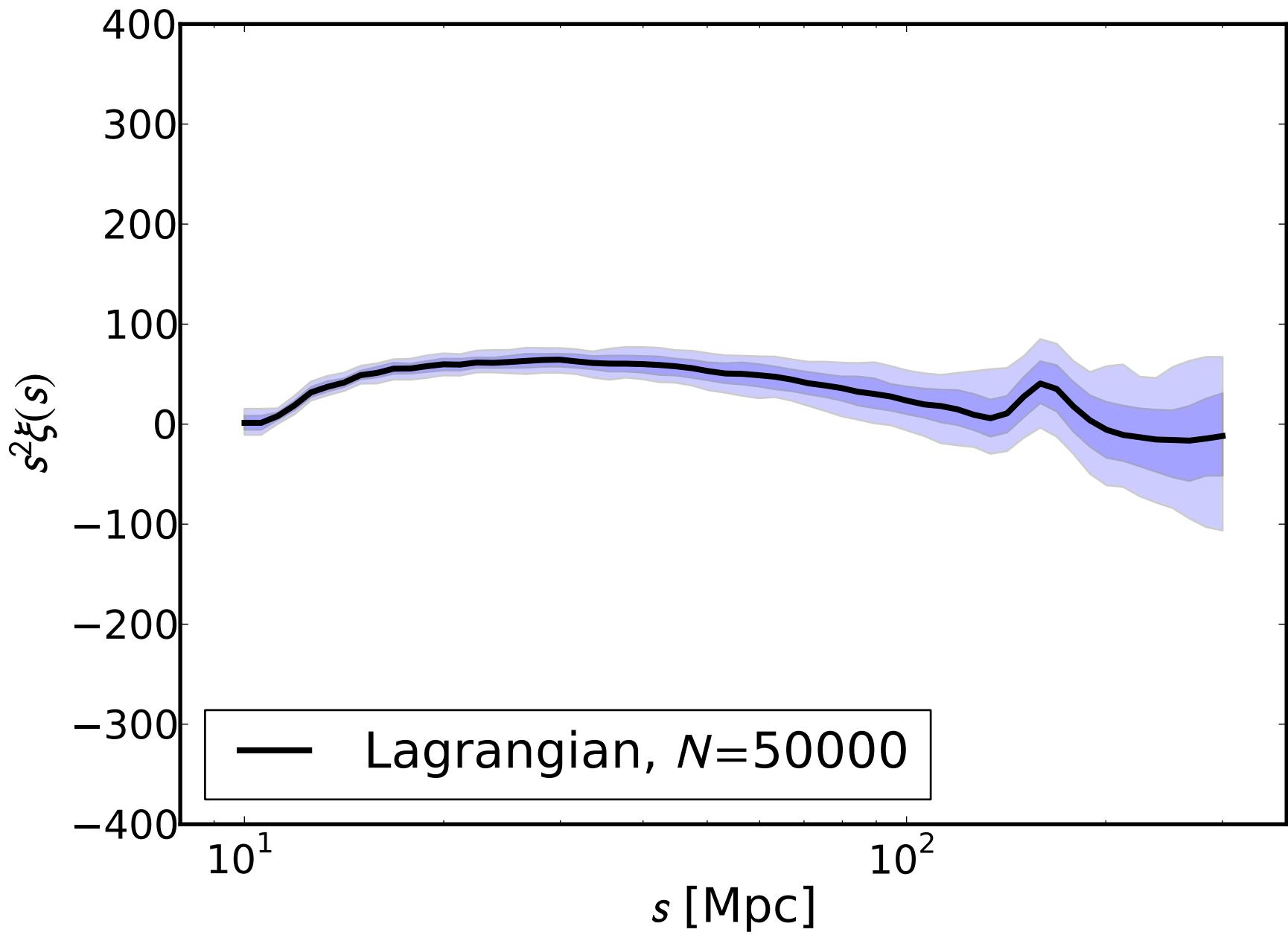
**Computed correlation function and its covariance**

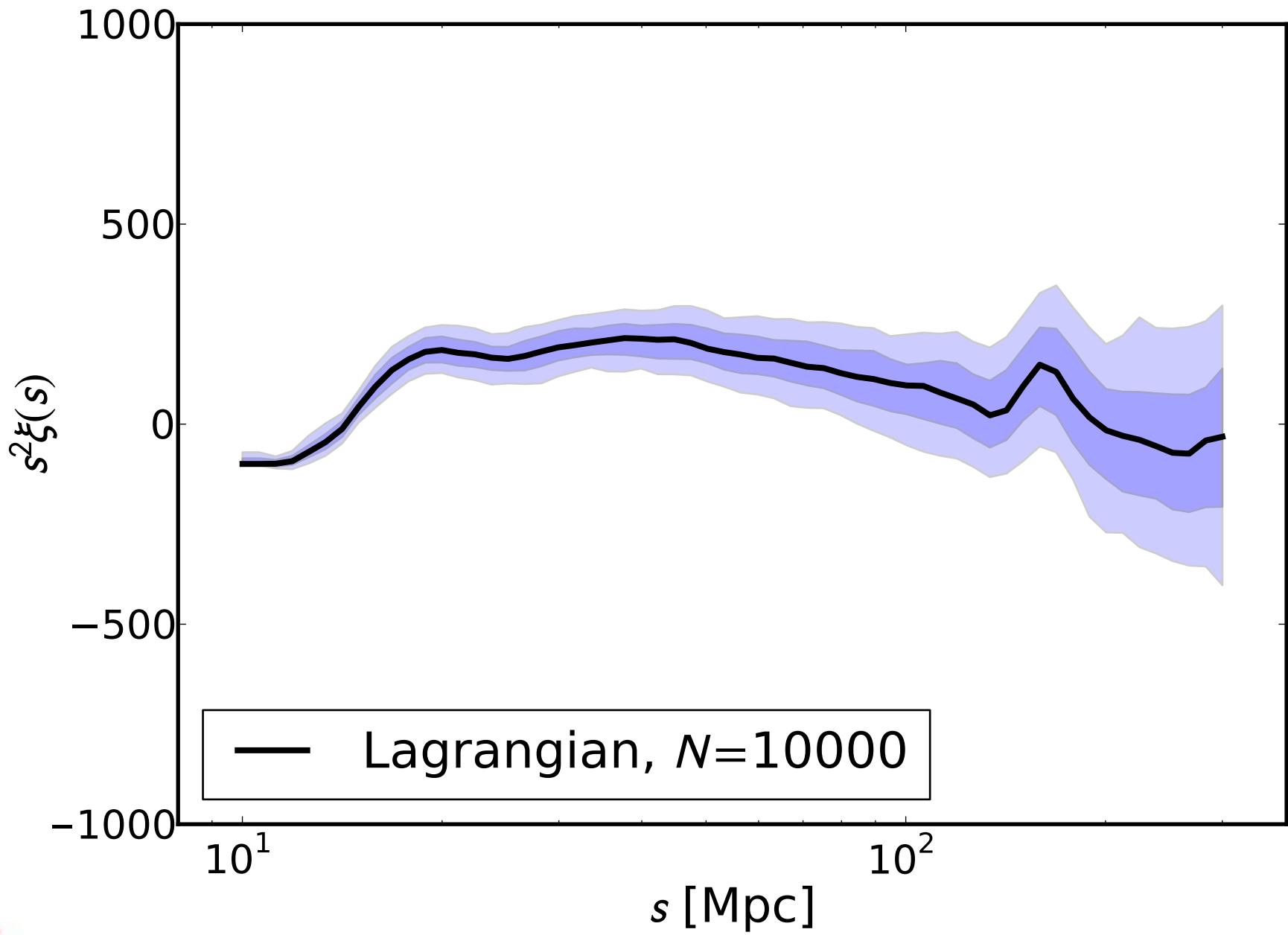


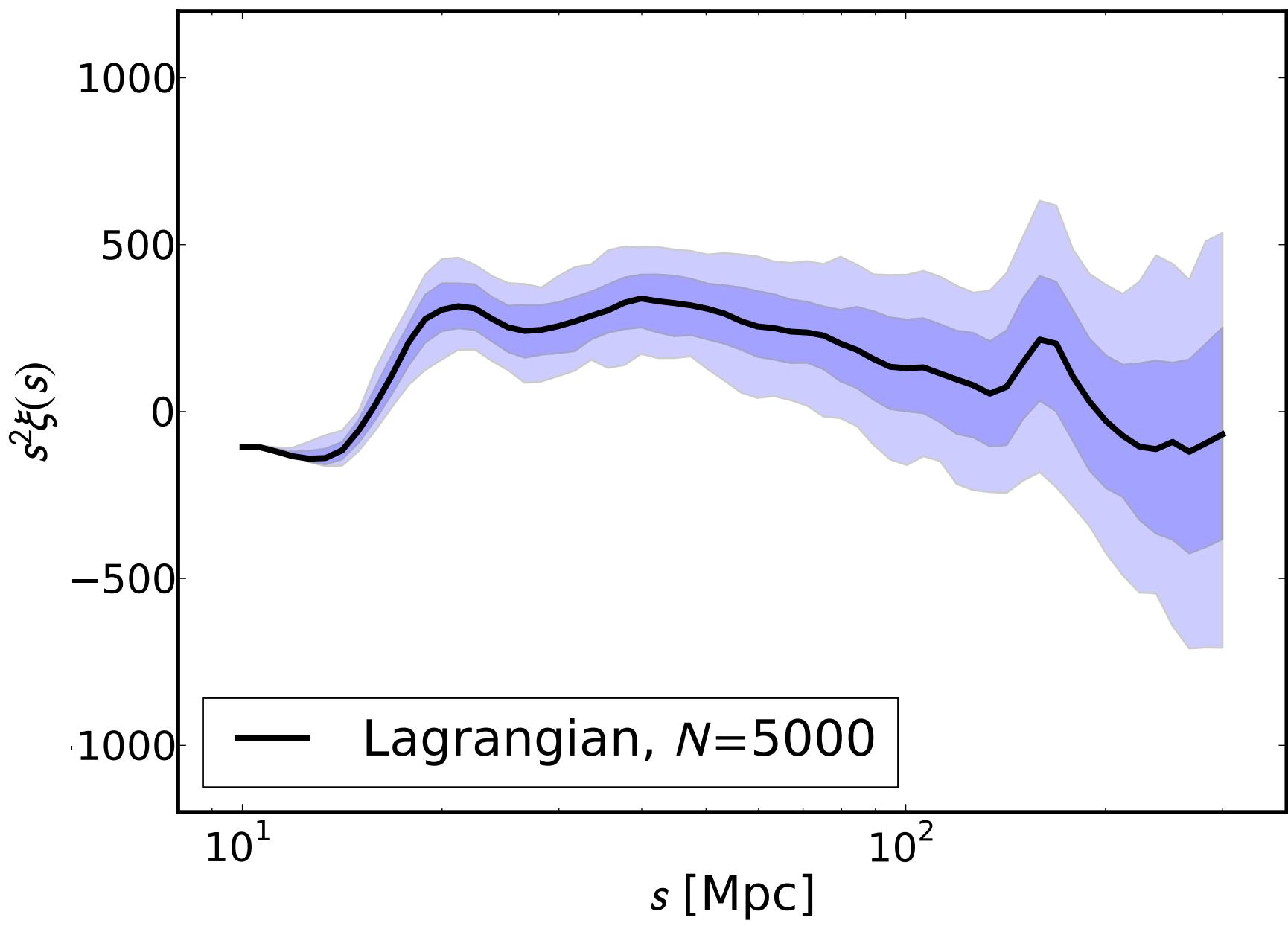
# Correlation Function in Lagrangian Coordinates

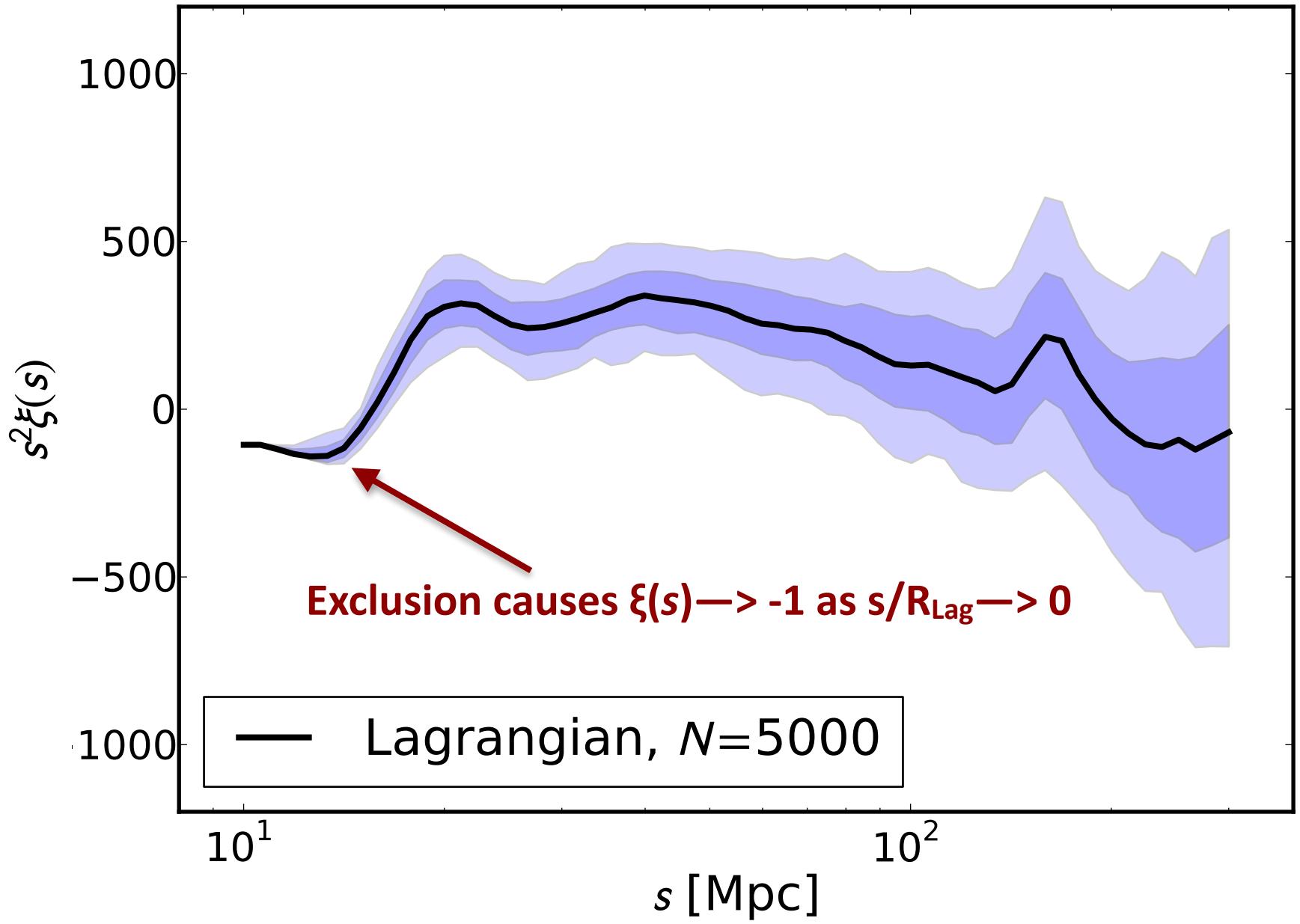


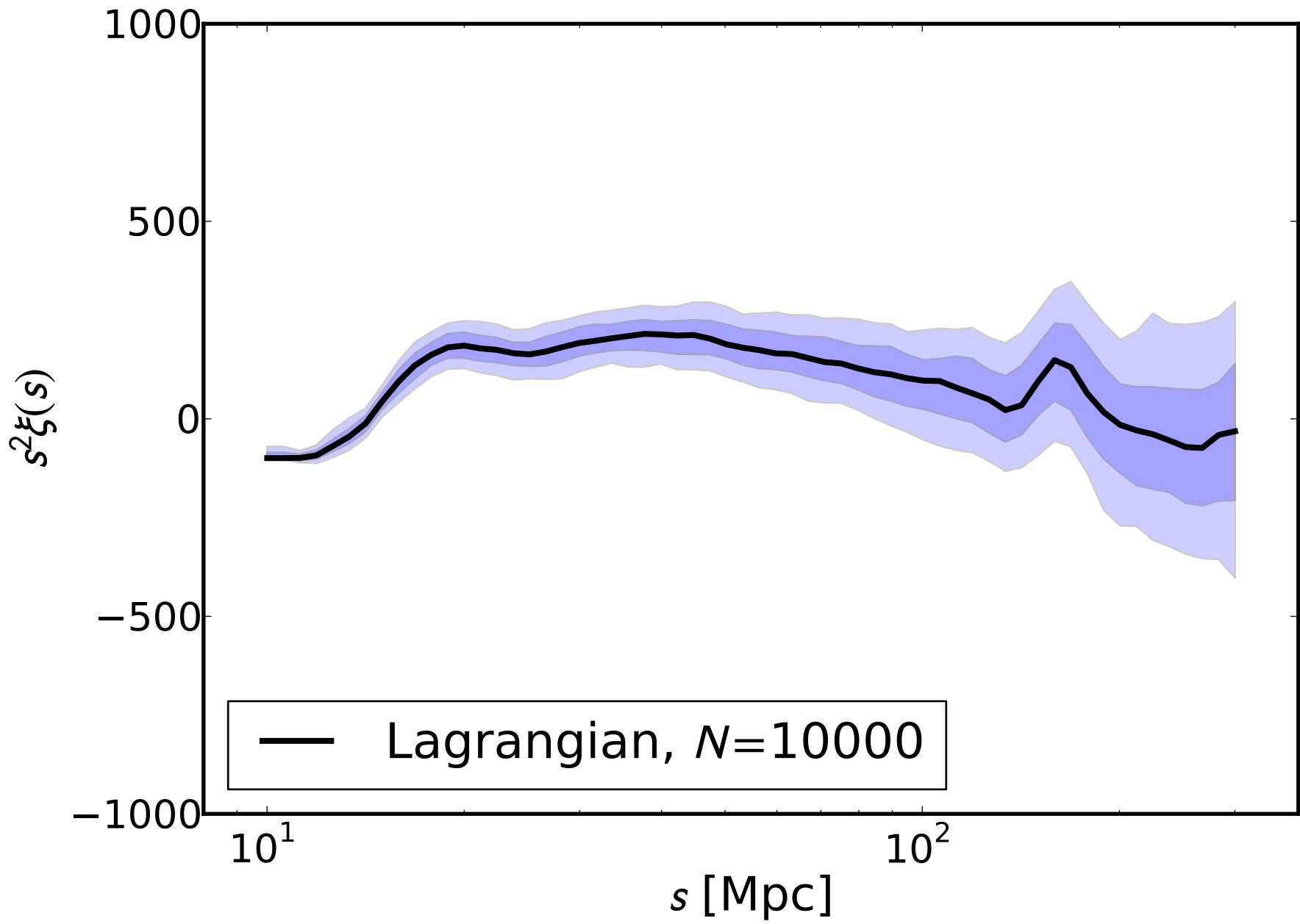


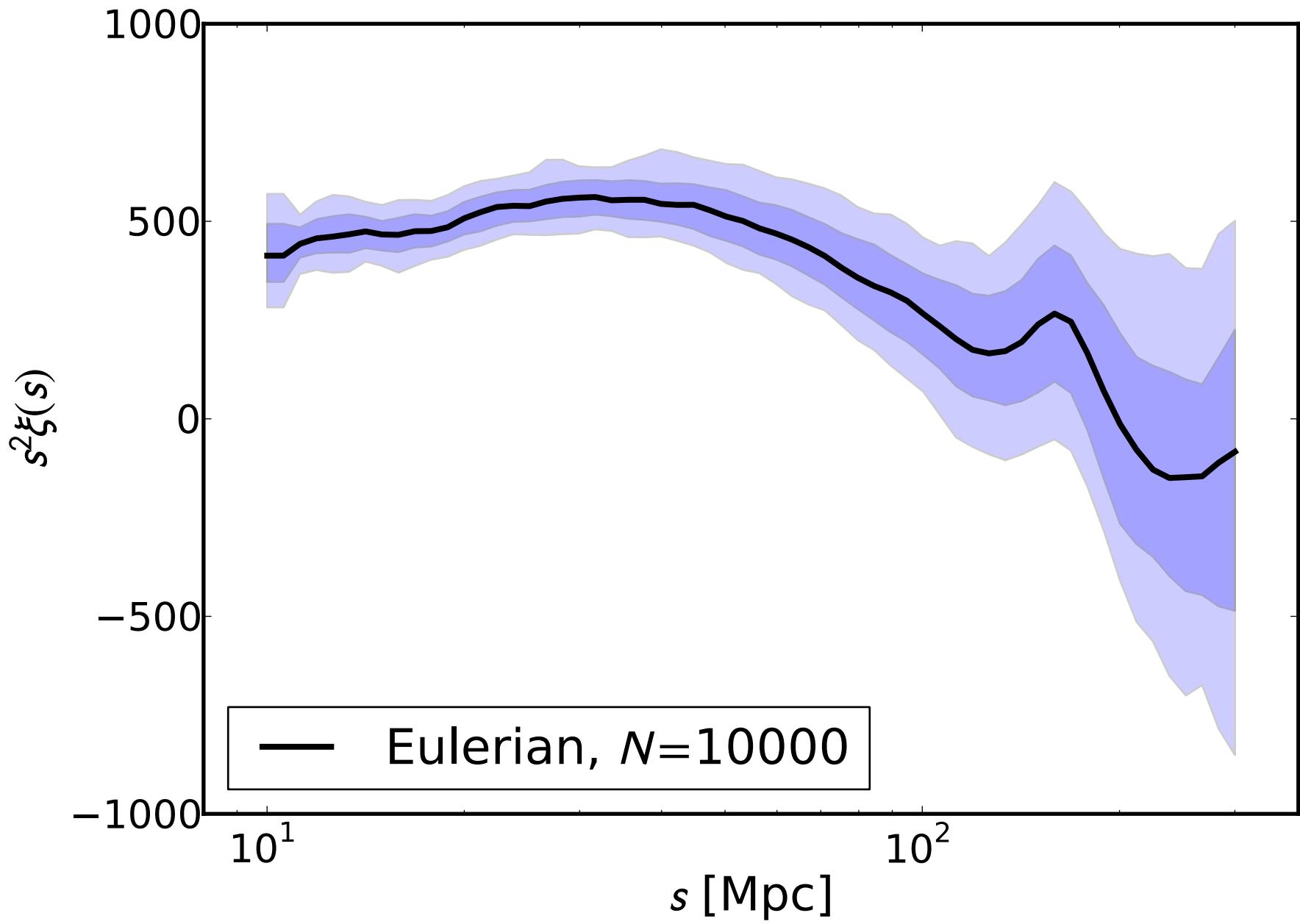








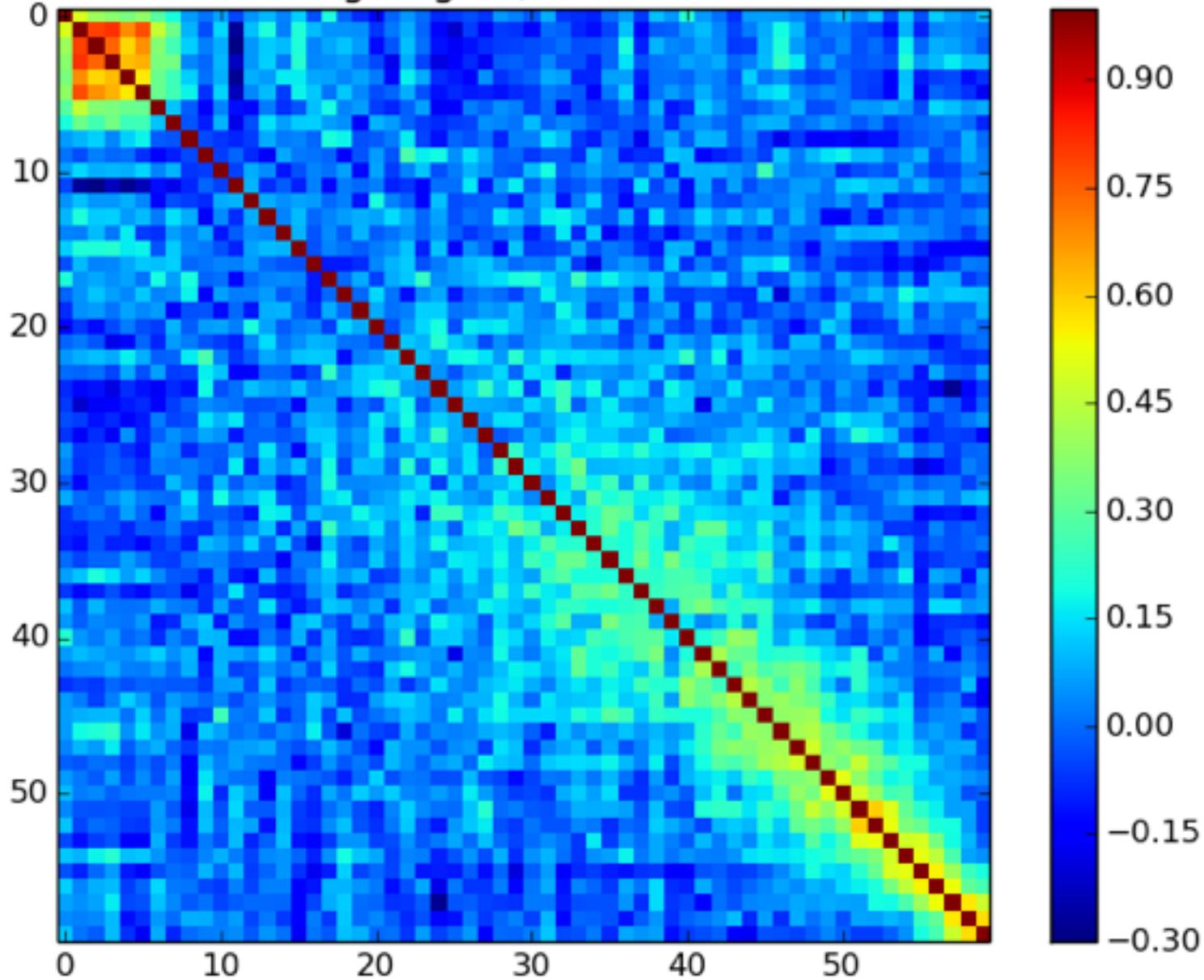




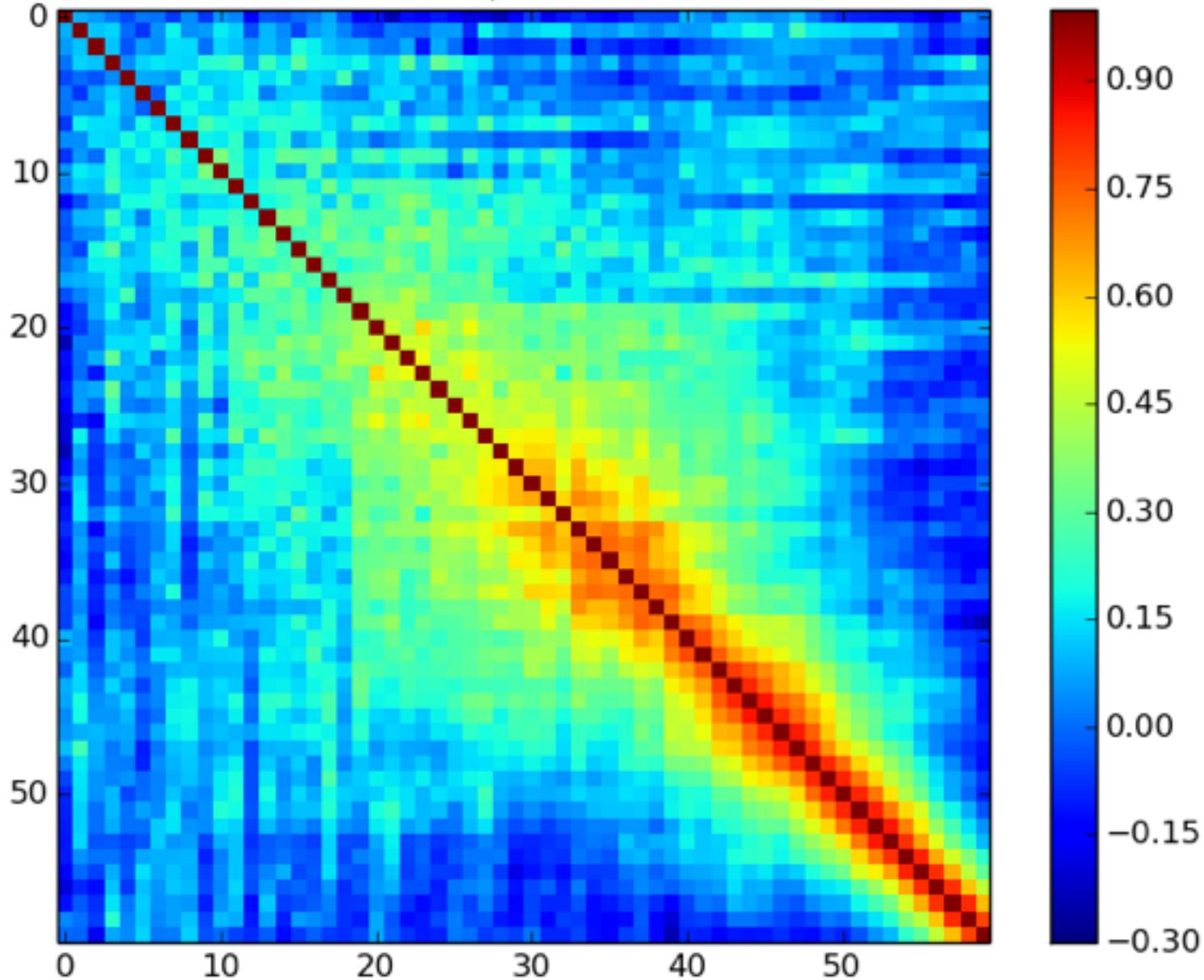
# Covariance of Correlation Function in Lagrangian & Eulerian Coordinates



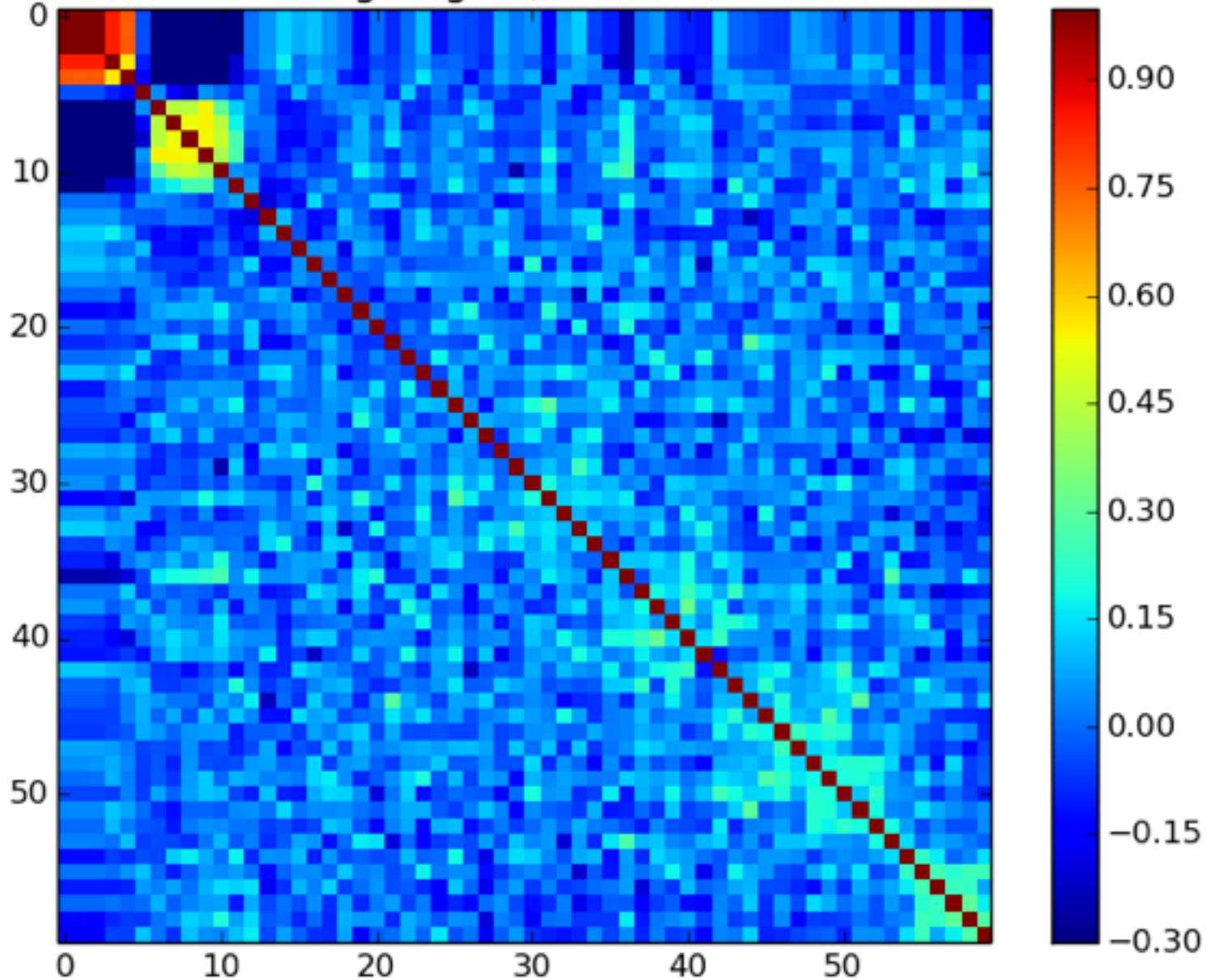
Lagrangian, N = 20000



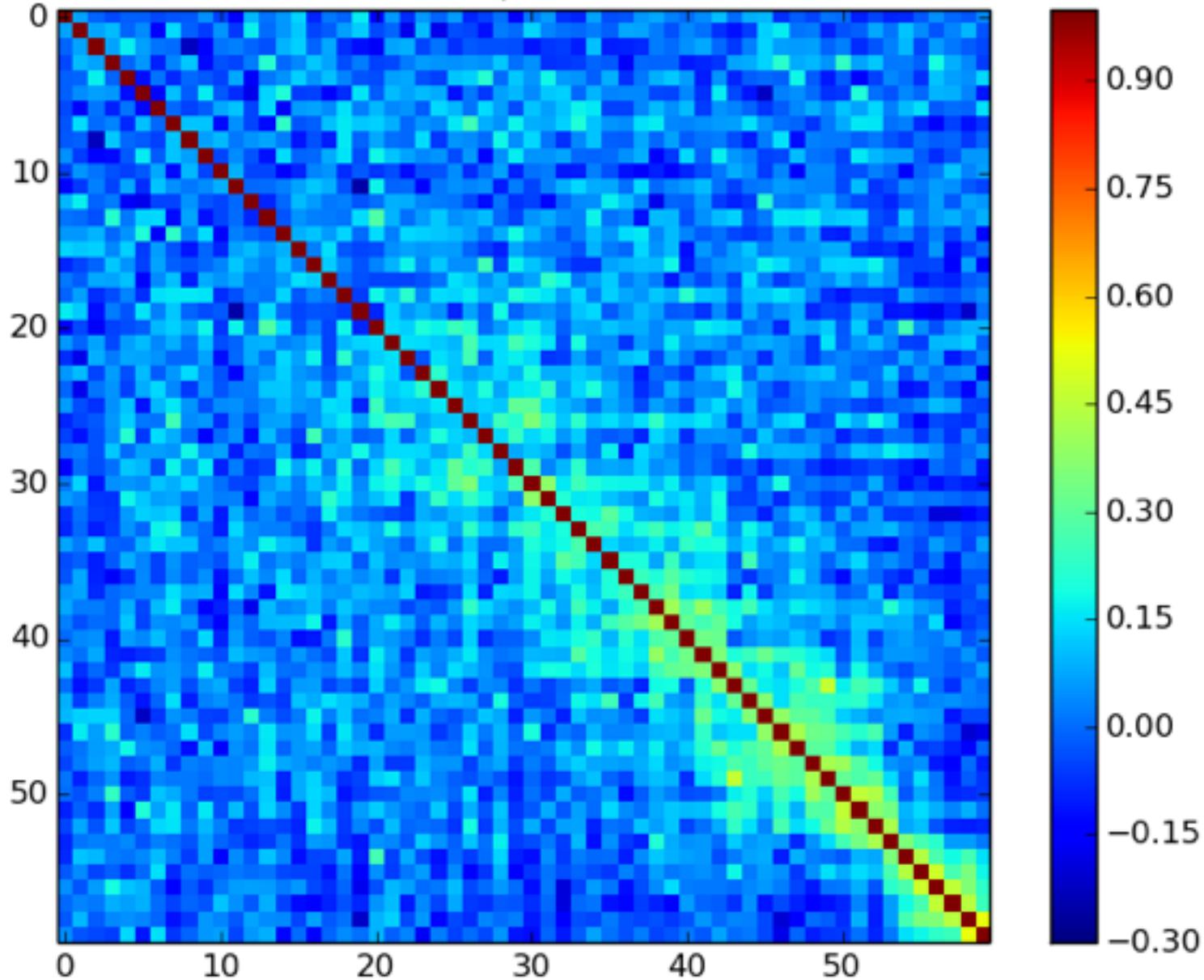
Eulerian, N = 20000



Lagrangian, N = 2000



Eulerian, N = 2000

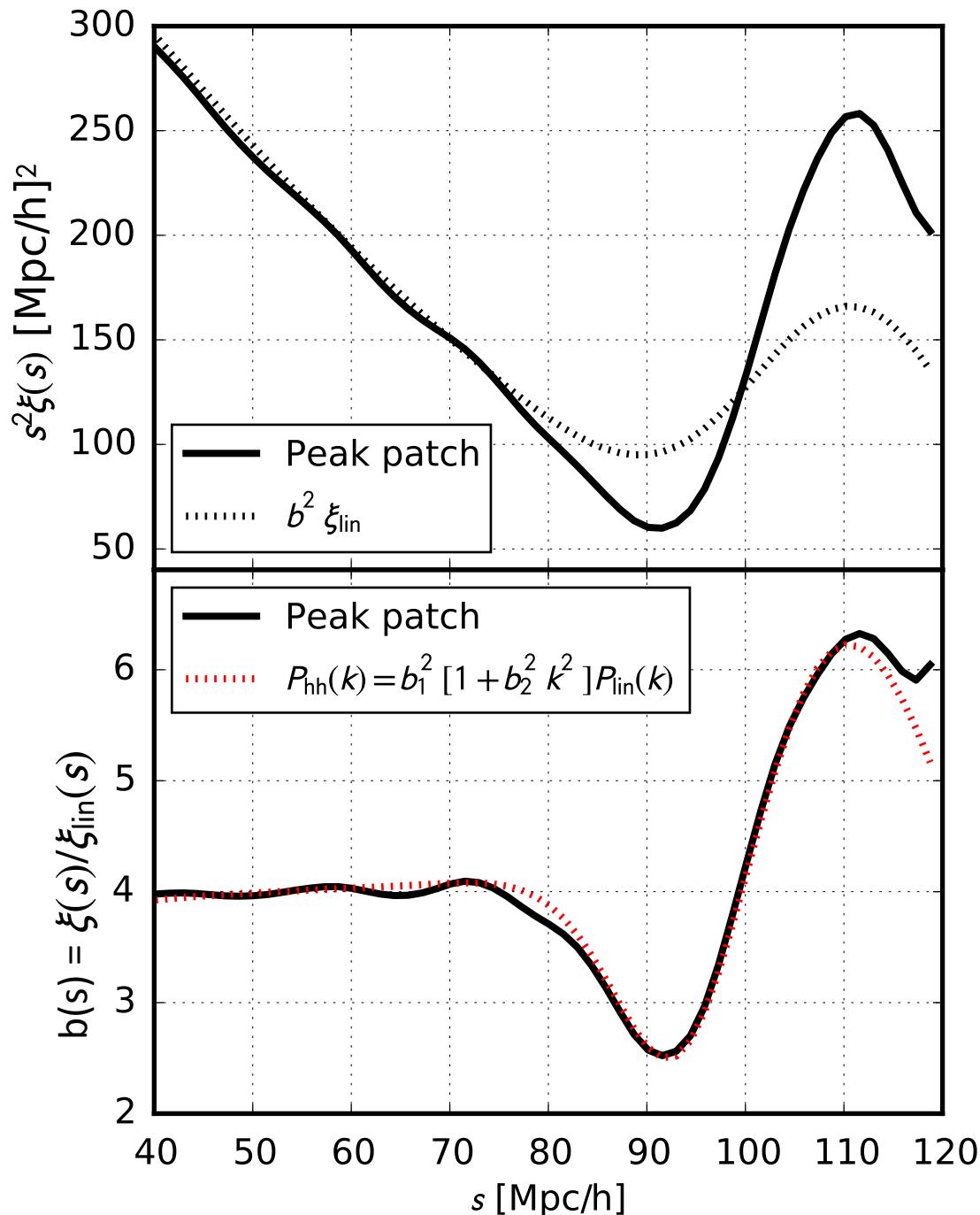


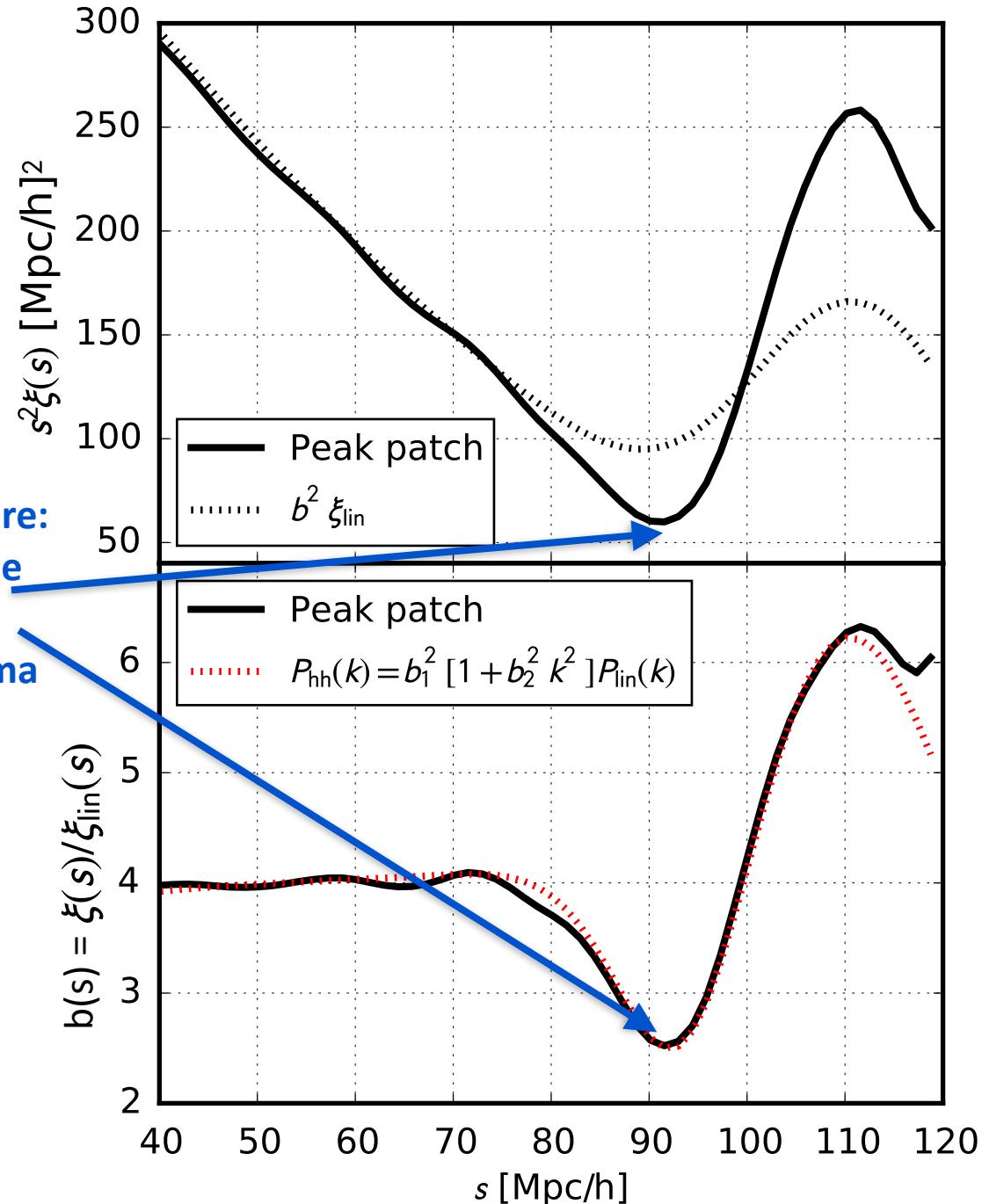
# The BAO Feature in Lagrangian Space

Box Size=1 Gpc  
 $N=1024^3$

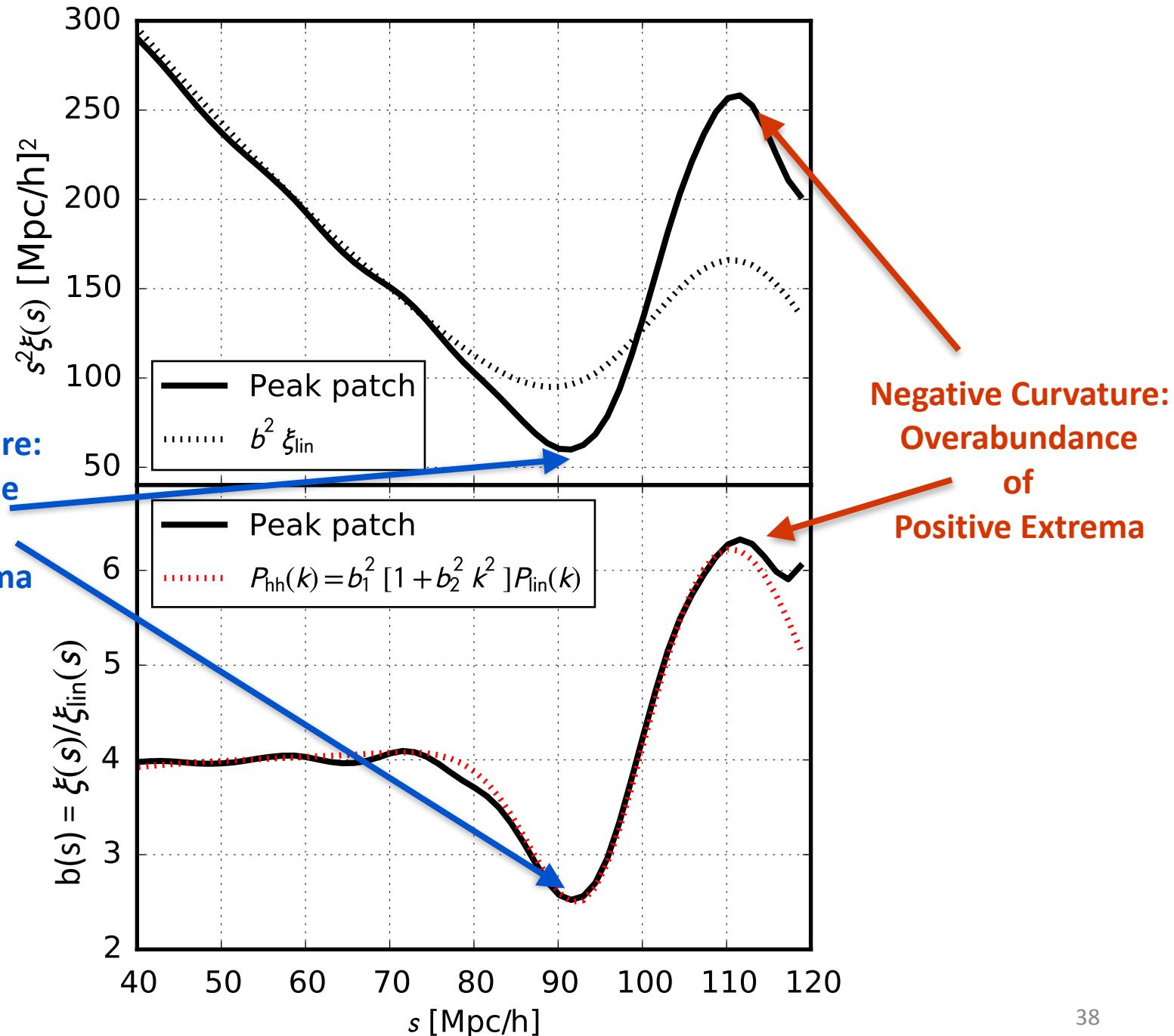
Mean of 400 Realizations







Positive Curvature:  
Overabundance  
of  
Negative Extrema

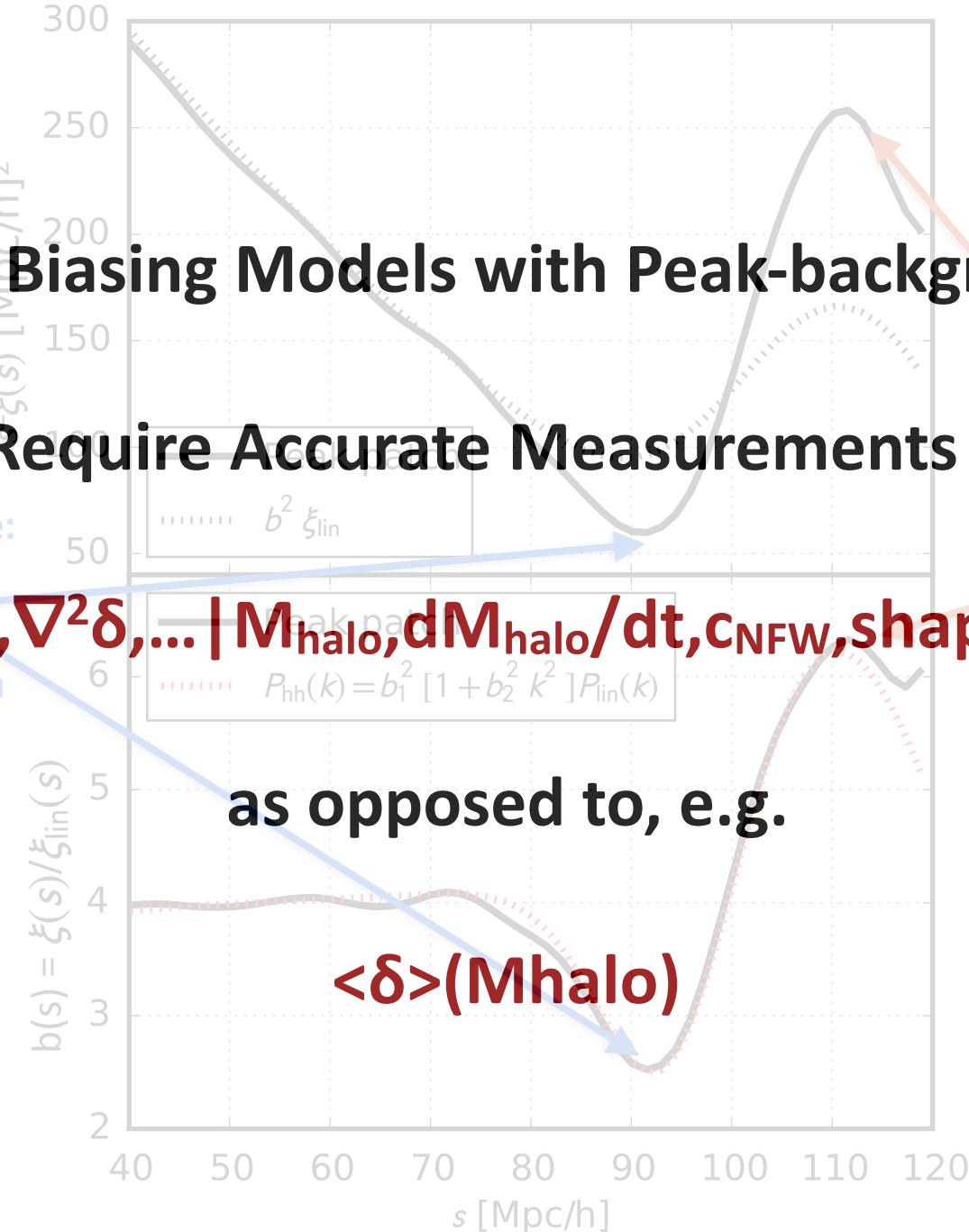


# Accurate Biassing Models with Peak-background Split

Require Accurate Measurements of

Positive Curvature:  
Overabundance  
of Negative Extrema

$p(\delta, \nabla^2\delta, \dots | M_{\text{halo}}, dM_{\text{halo}}/dt, c_{\text{NFW}}, \text{shape}, \dots)$



Negative Curvature:  
Overabundance  
of Positive Extrema

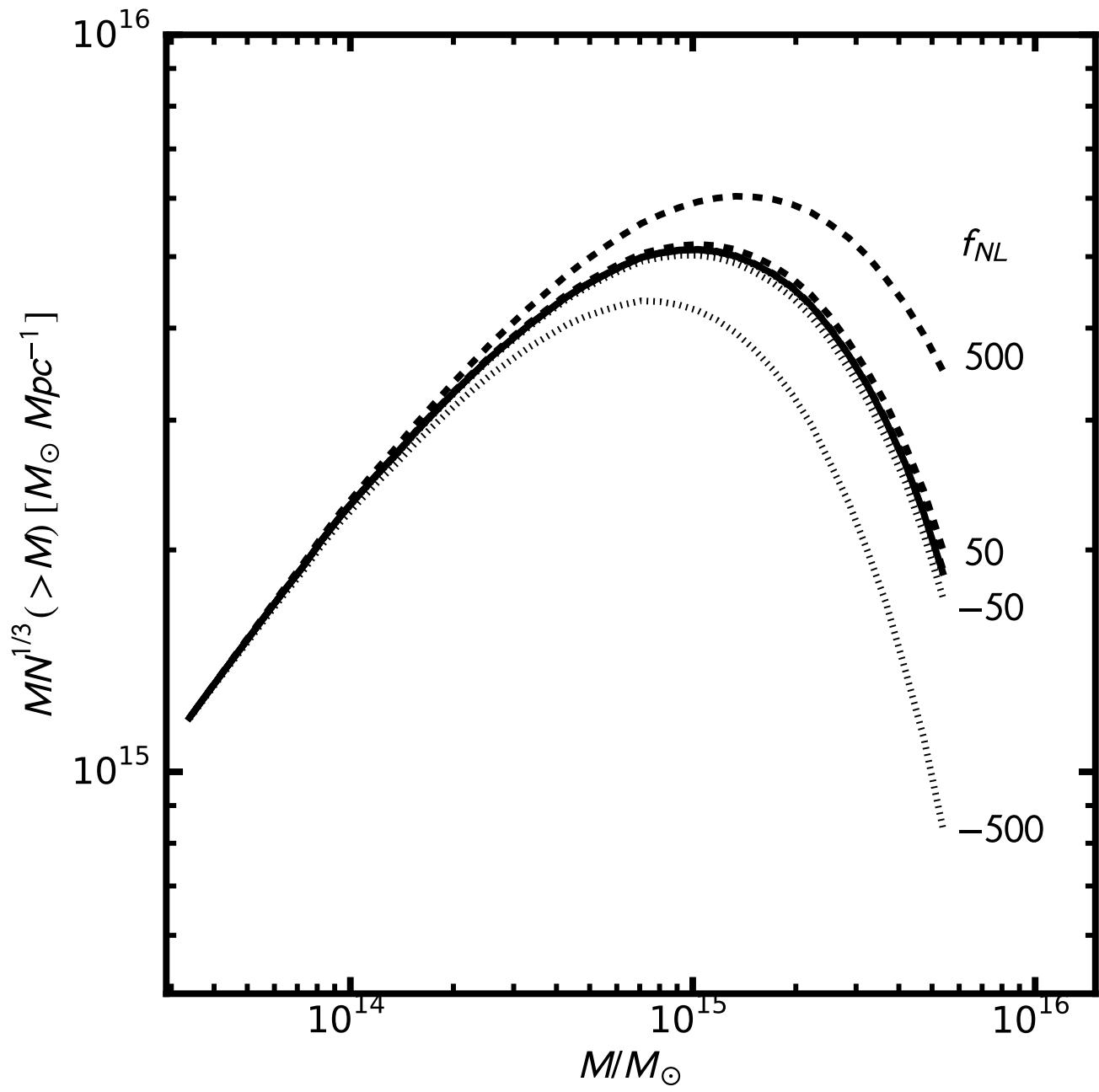
# Local-type Non-Gaussianity

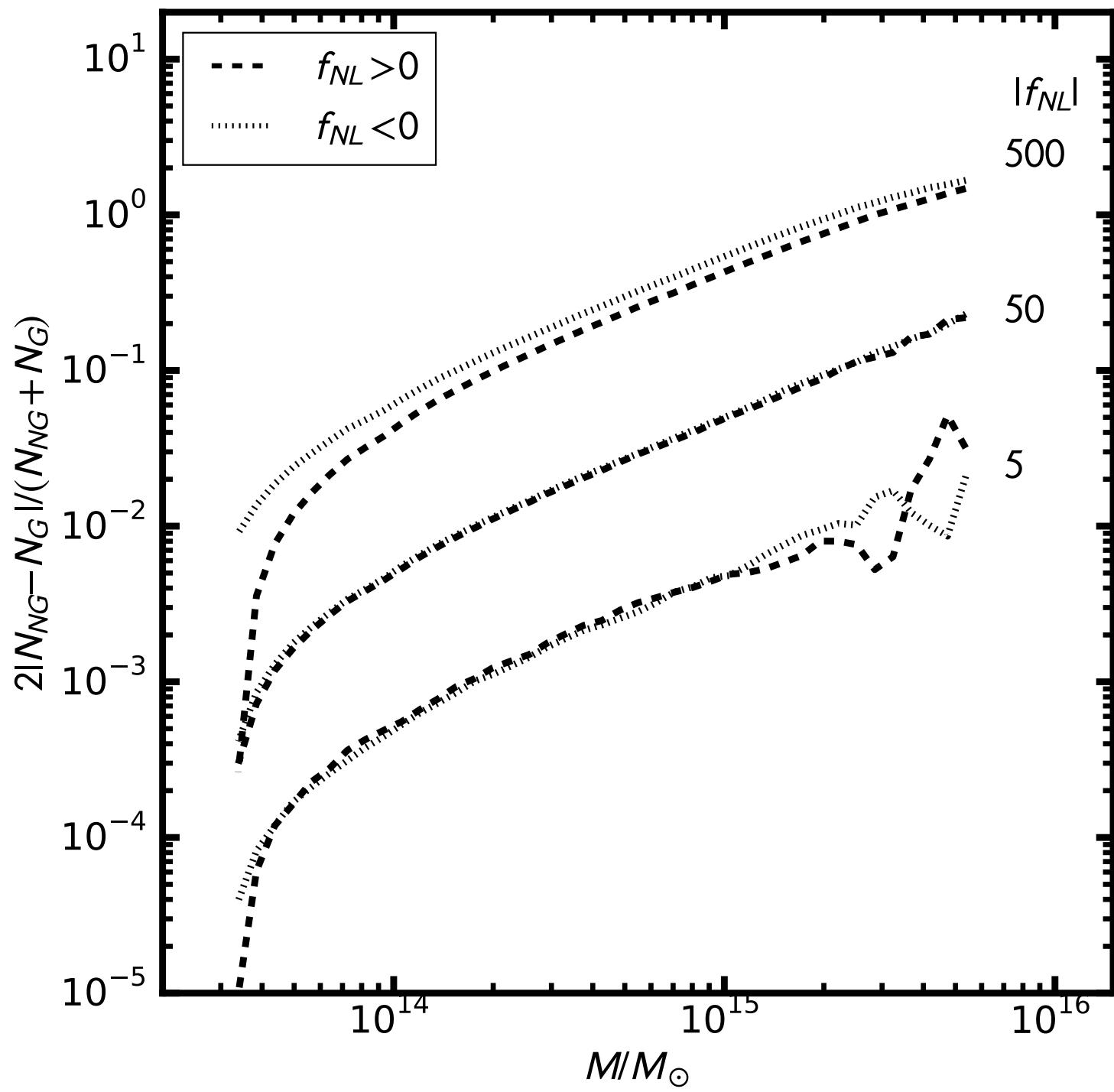
Box Size=2 Gpc  
 $N=1024^3$

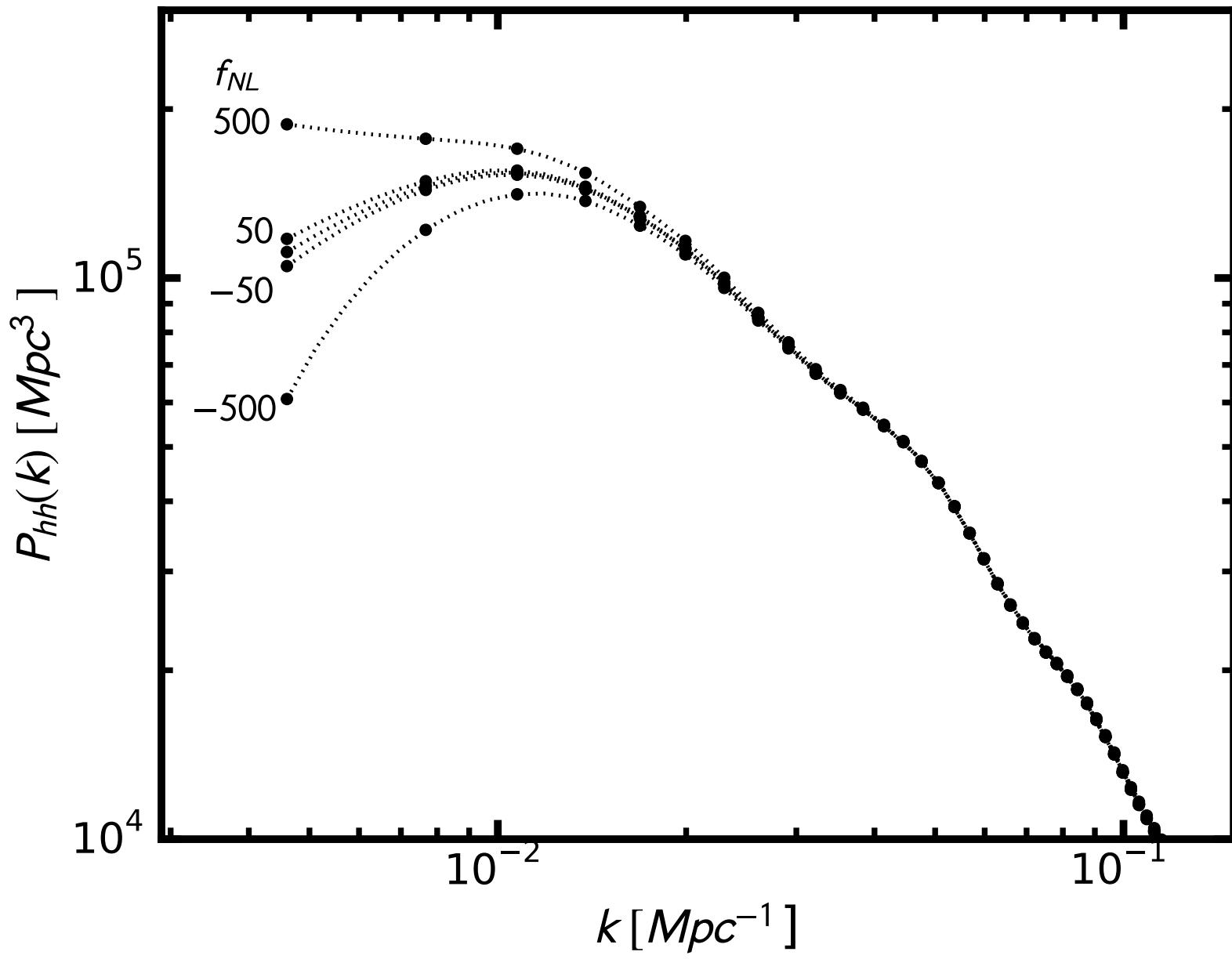
$f_{NL} = -500, -50, -5, 0, 5, 50, 500$

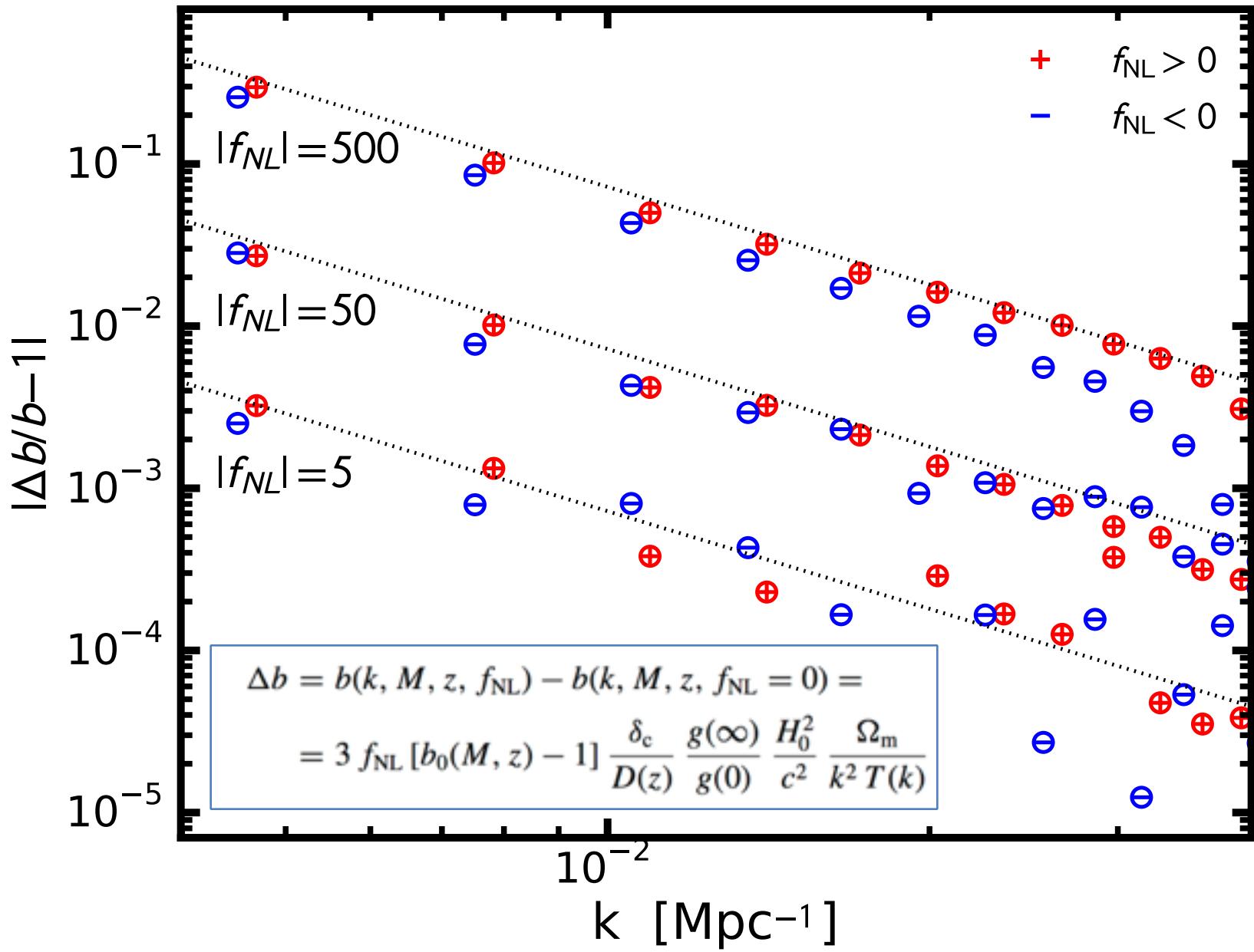
Mean of 800 Realizations



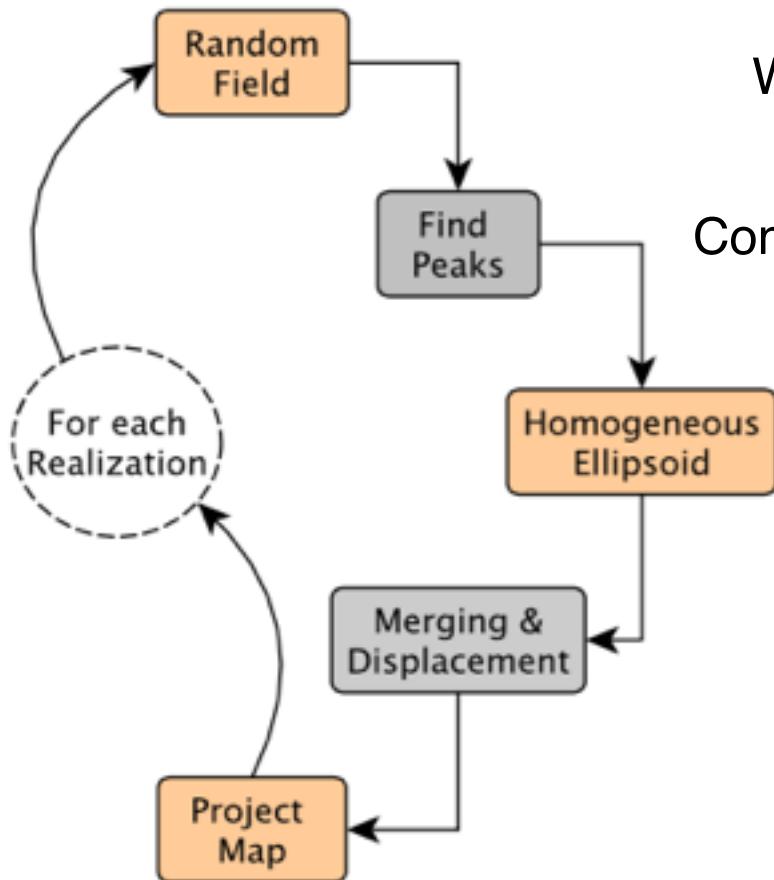








# Case Study of Simulation Pipeline: Full Sky Cluster tSZ Mocks



8 Gpc box —  $4096^3$  cells

Wall clock ~ **10 mins** each on 1024 cores

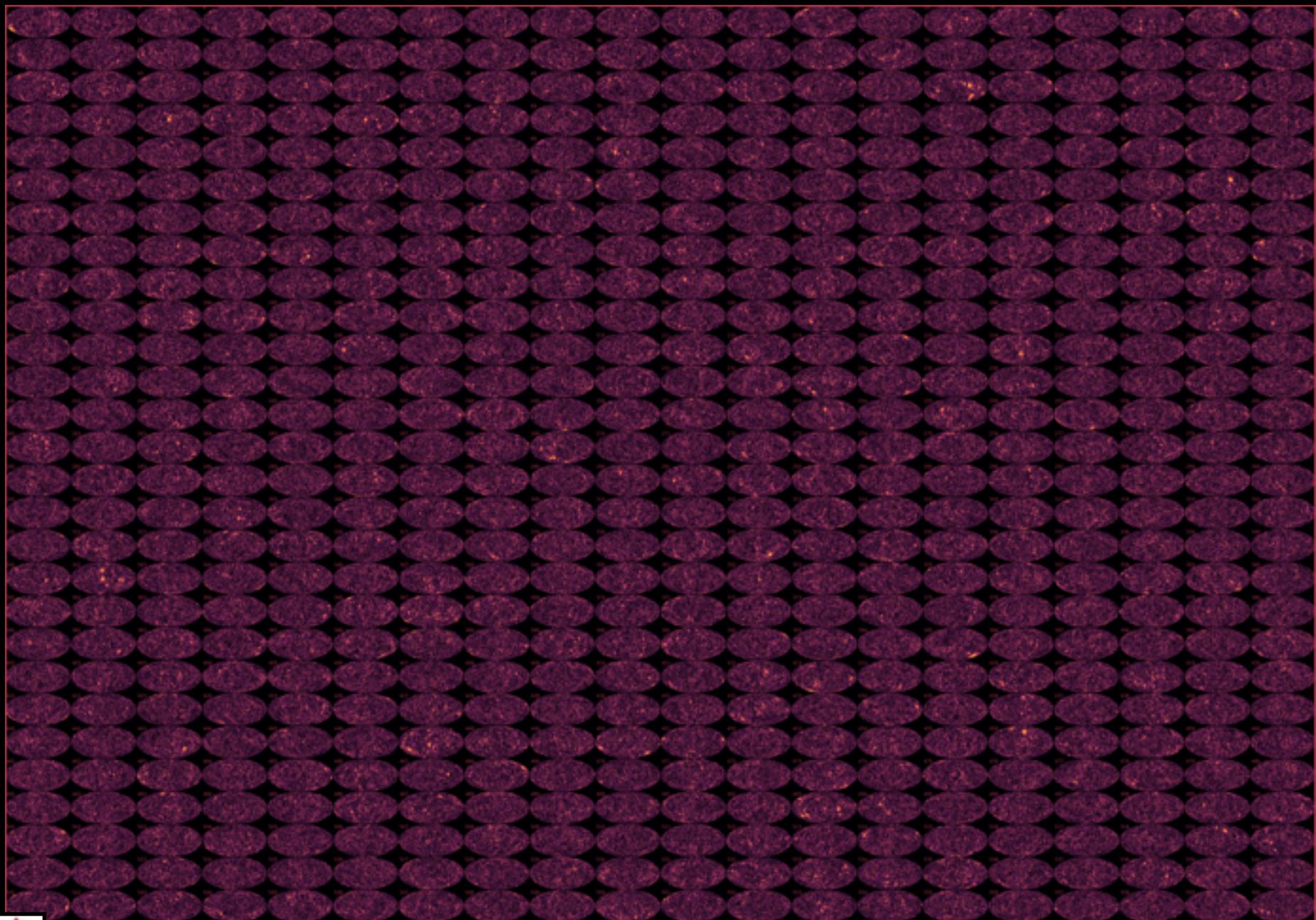
Full-sky Light Cone with ~  **$6 \times 10^7$  halos**

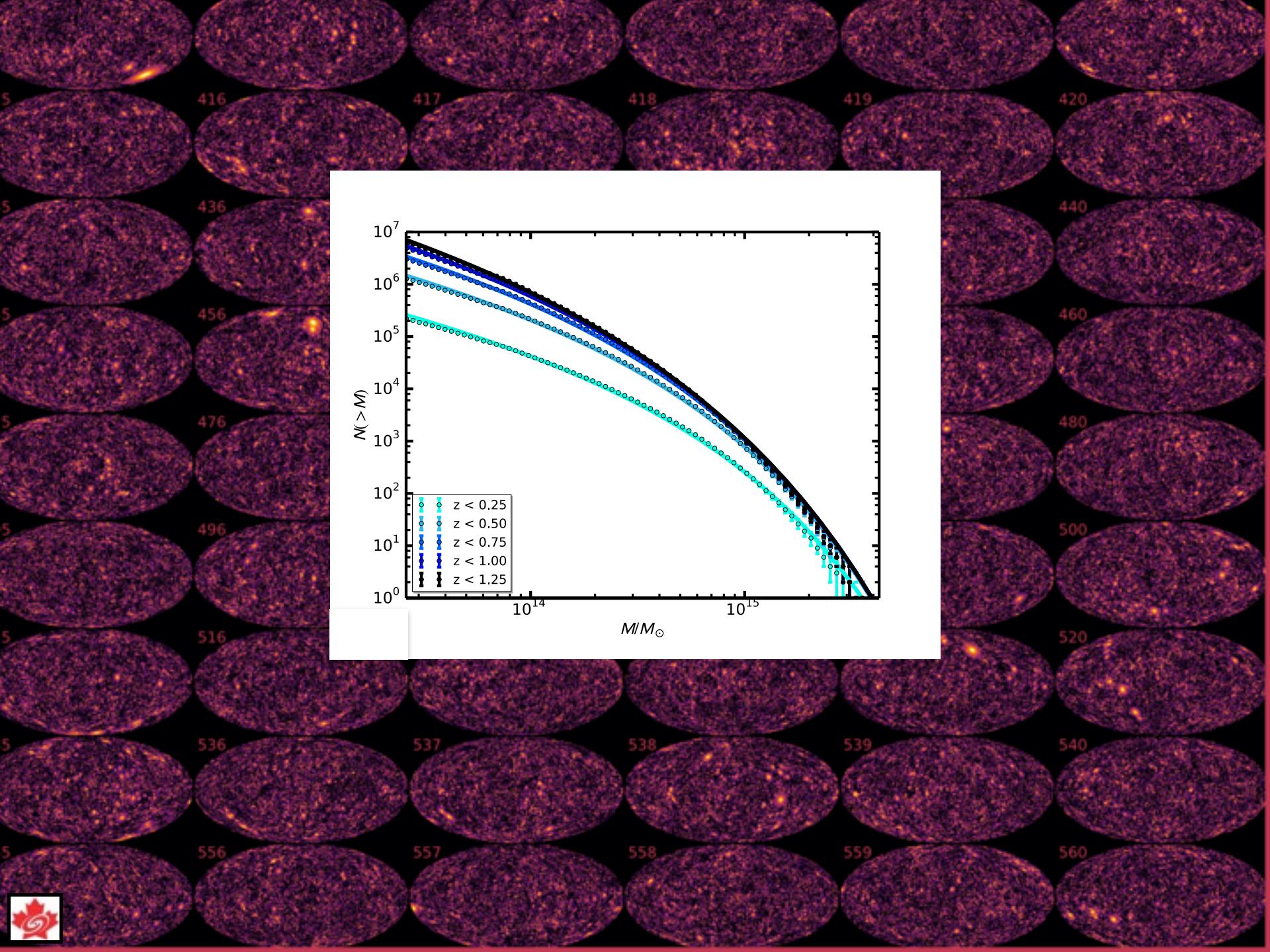
Complete to  $z < 1.3$  and  $M_{\text{halo}} > 3 \times 10^{13} M_{\odot}$

~ **500 maps produced total**

Battaglia et al. (2012) universal pressure profile out to  $4R_{200}$

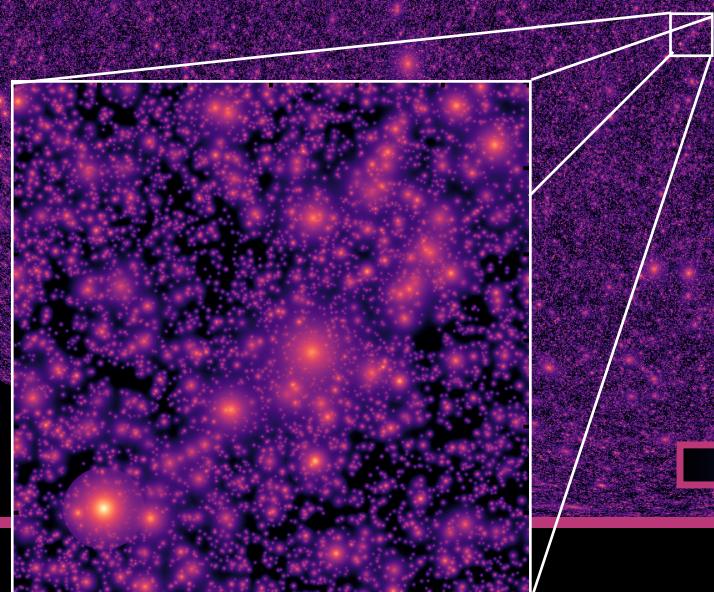






$0.00 < z < 1.25$   
 $8\text{Gpc}, 4096^3 \text{ Box}$   
 $N = 6.5 \times 10^6$

tSZ



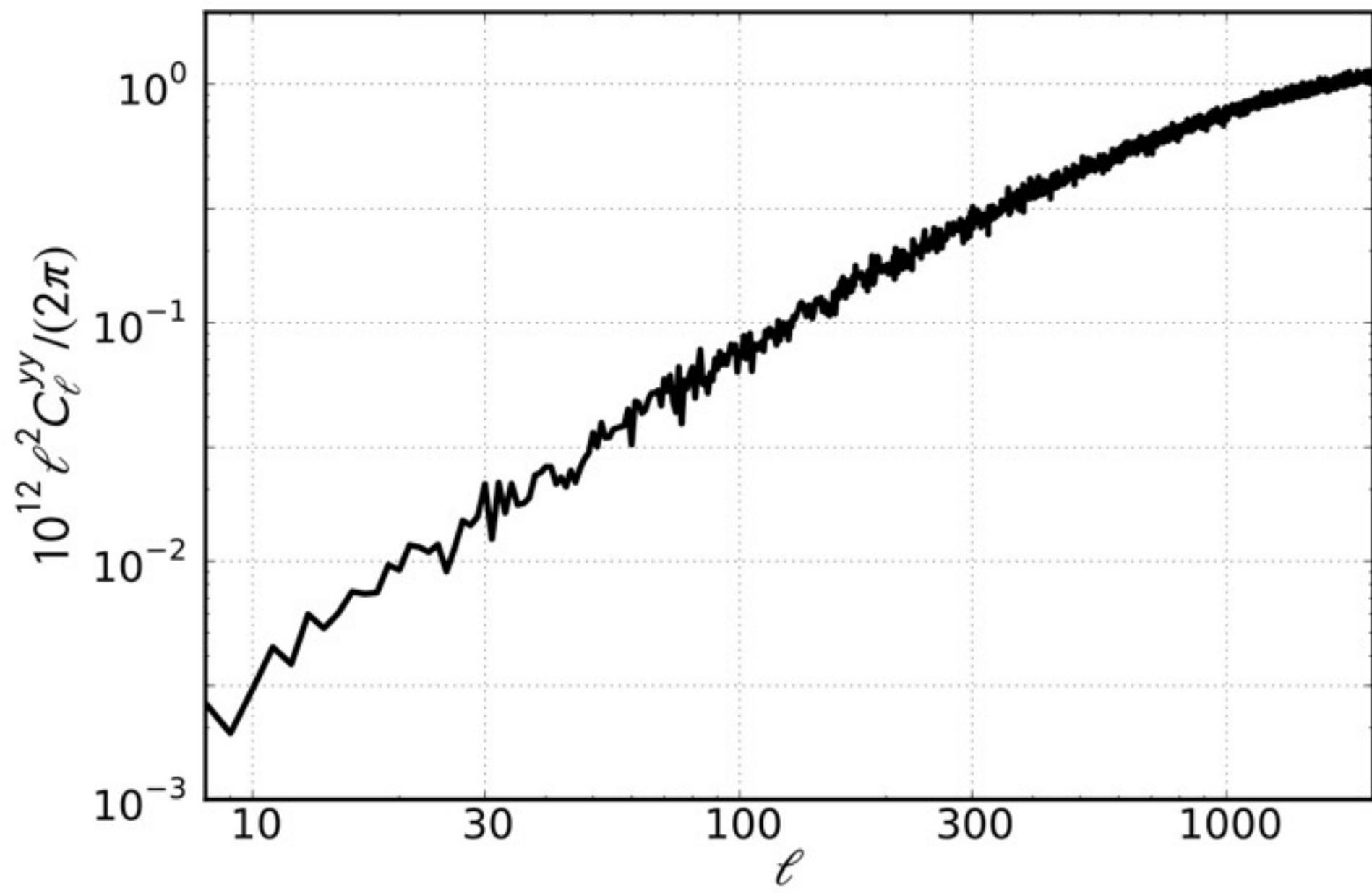
log Compton-y

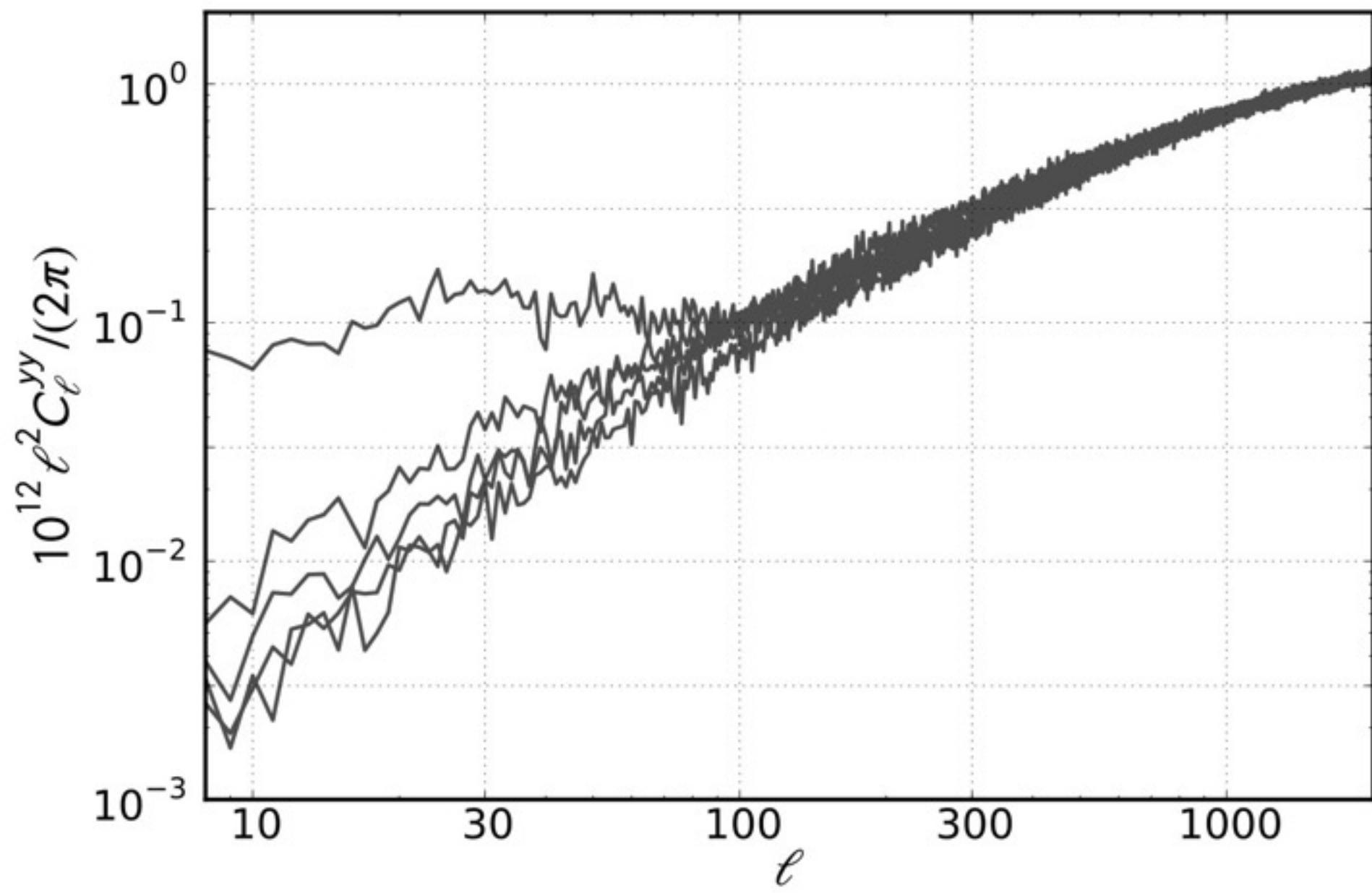
-7.5 -7.0 -6.5 -6.0 -5.5 -5.0 -4.5 -4.0

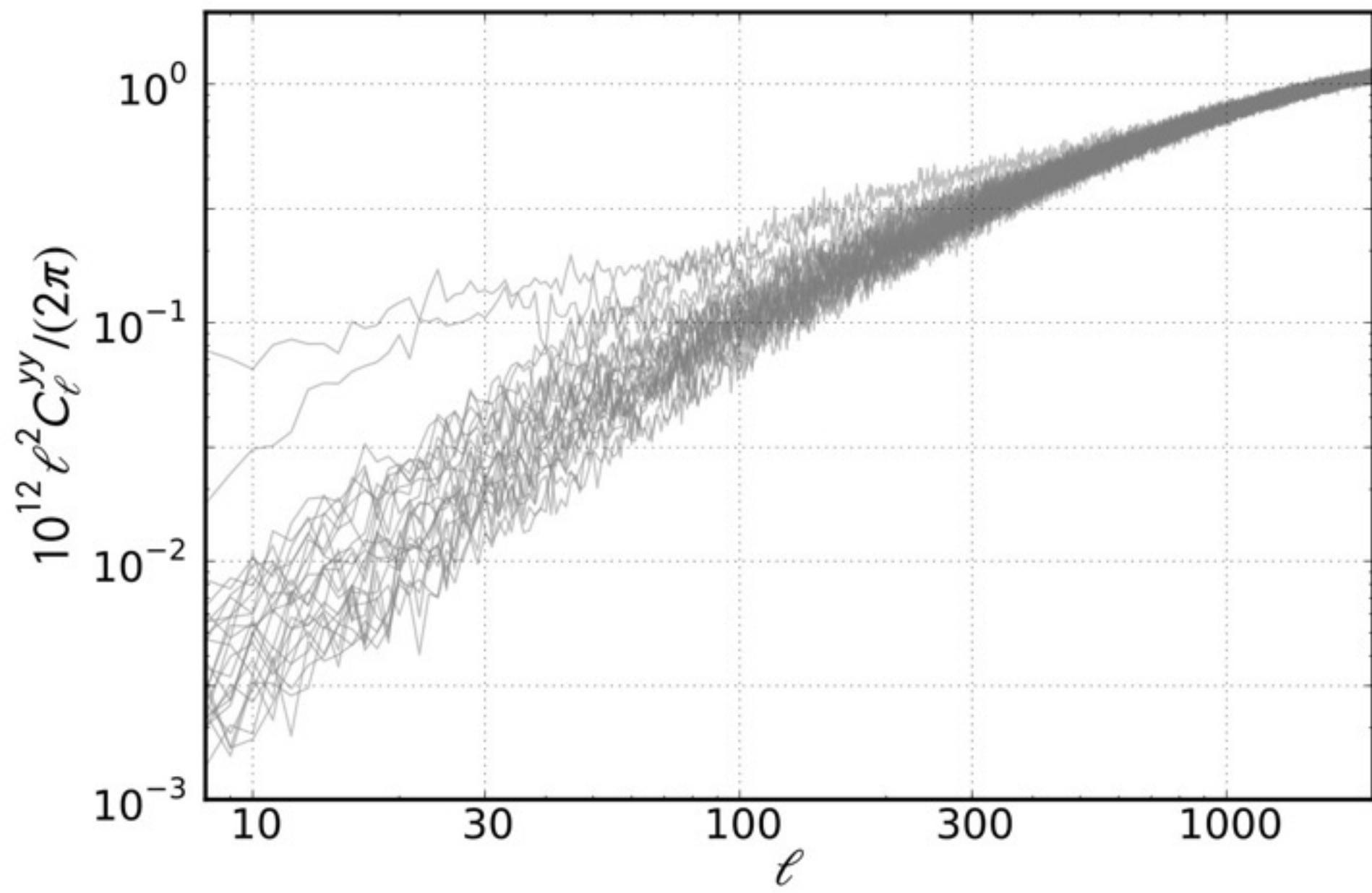


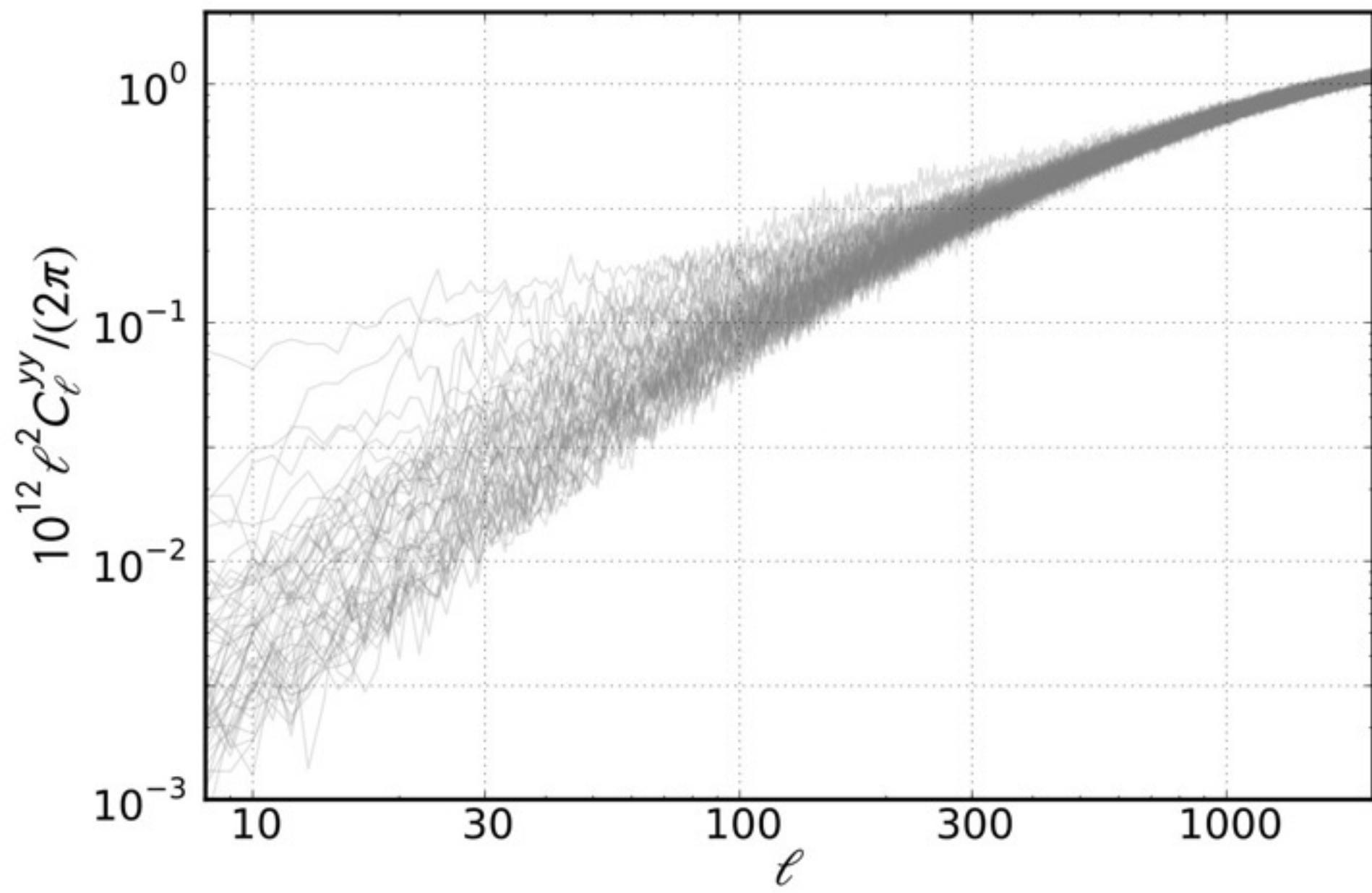
# Statistics of Cluster tSZ (y-map) Angular Power Spectrum

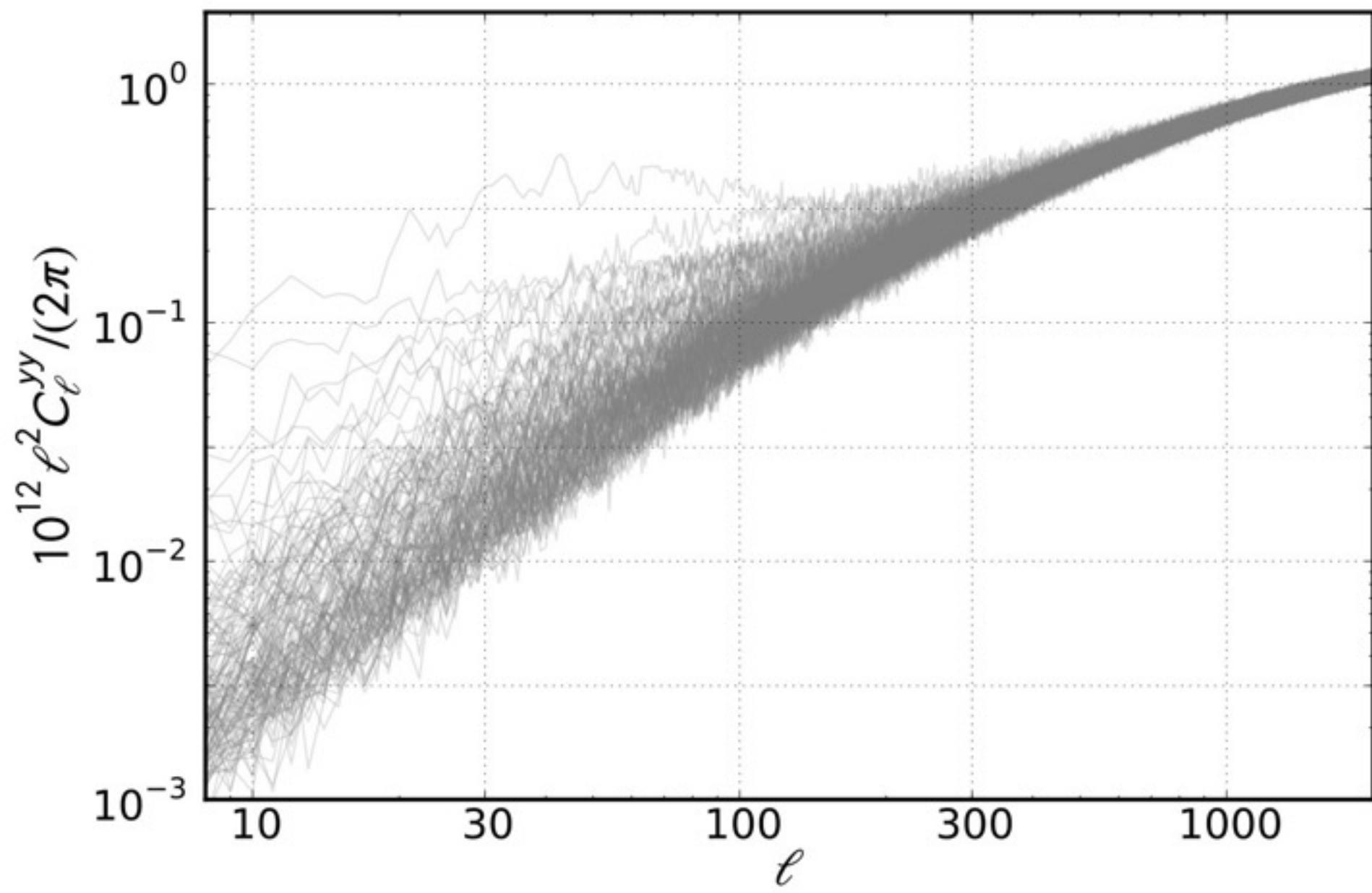


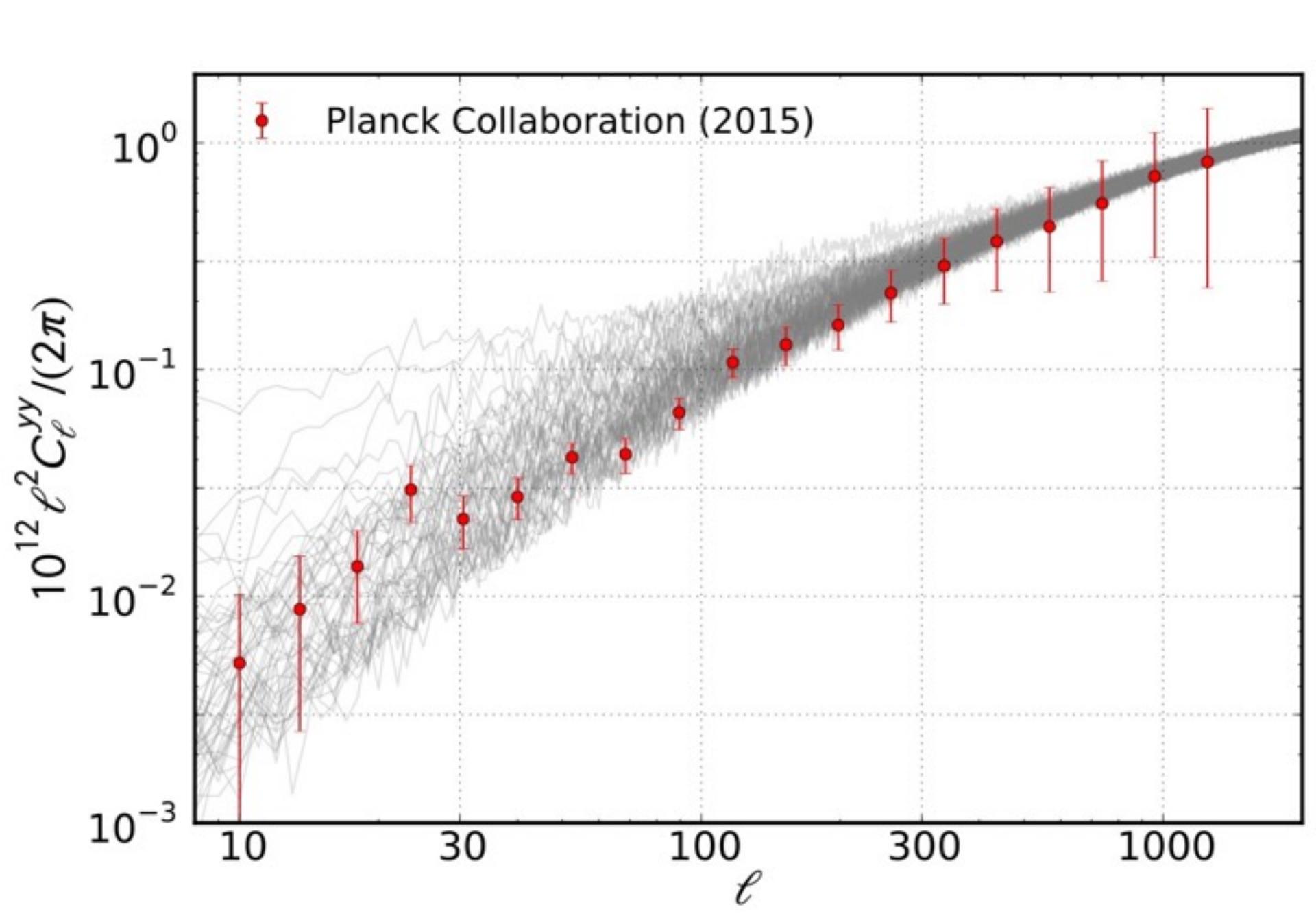


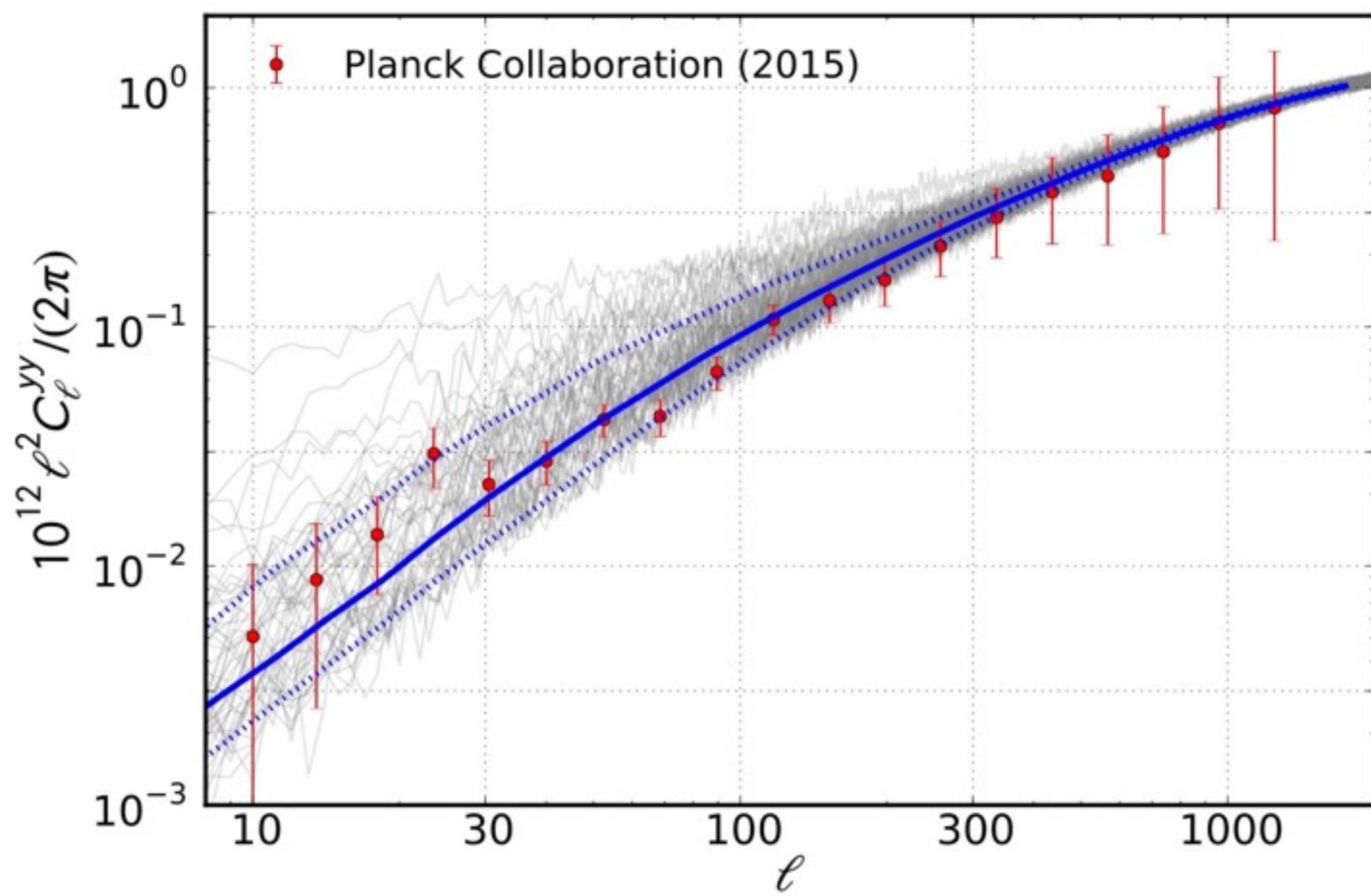


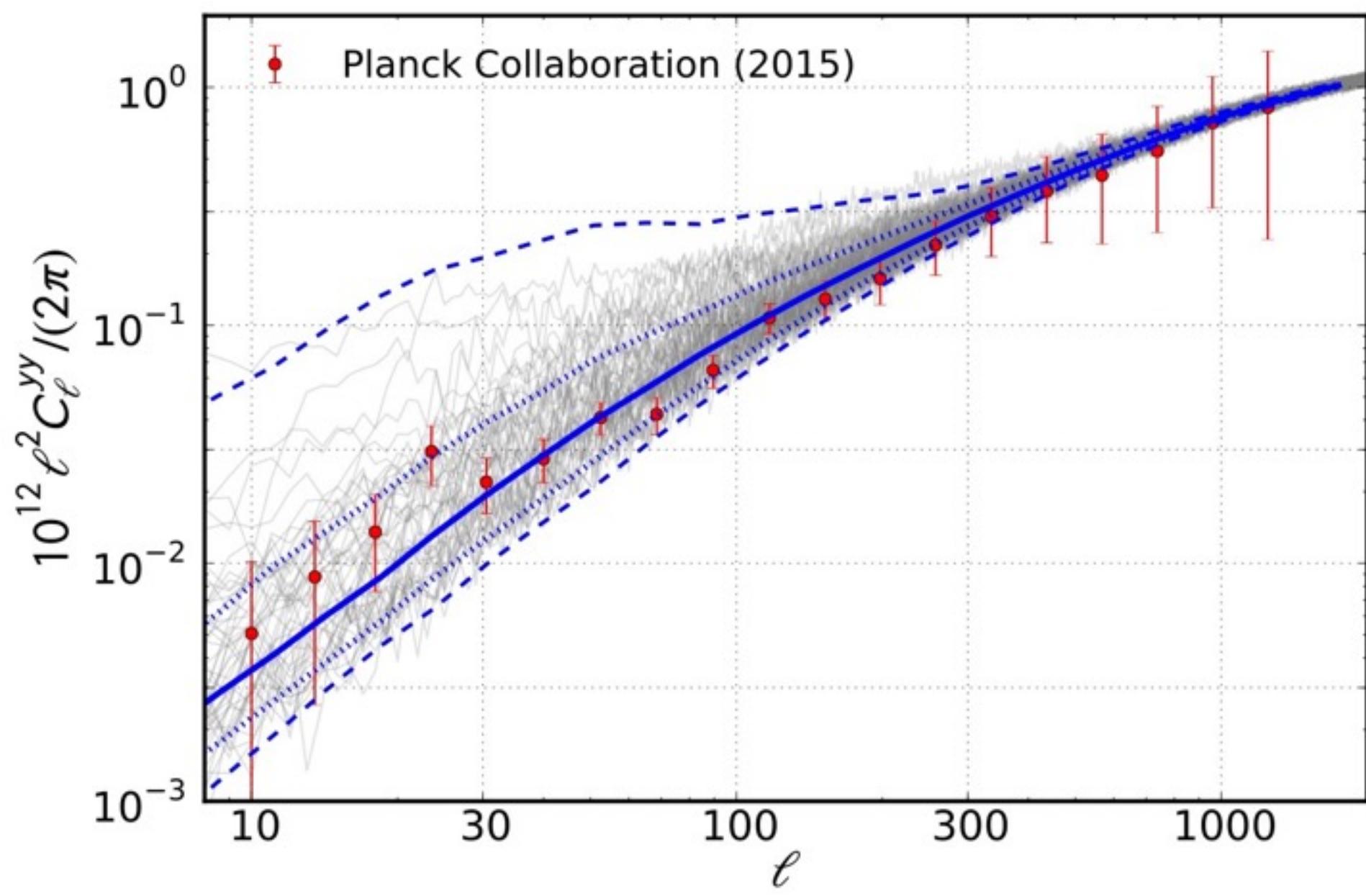










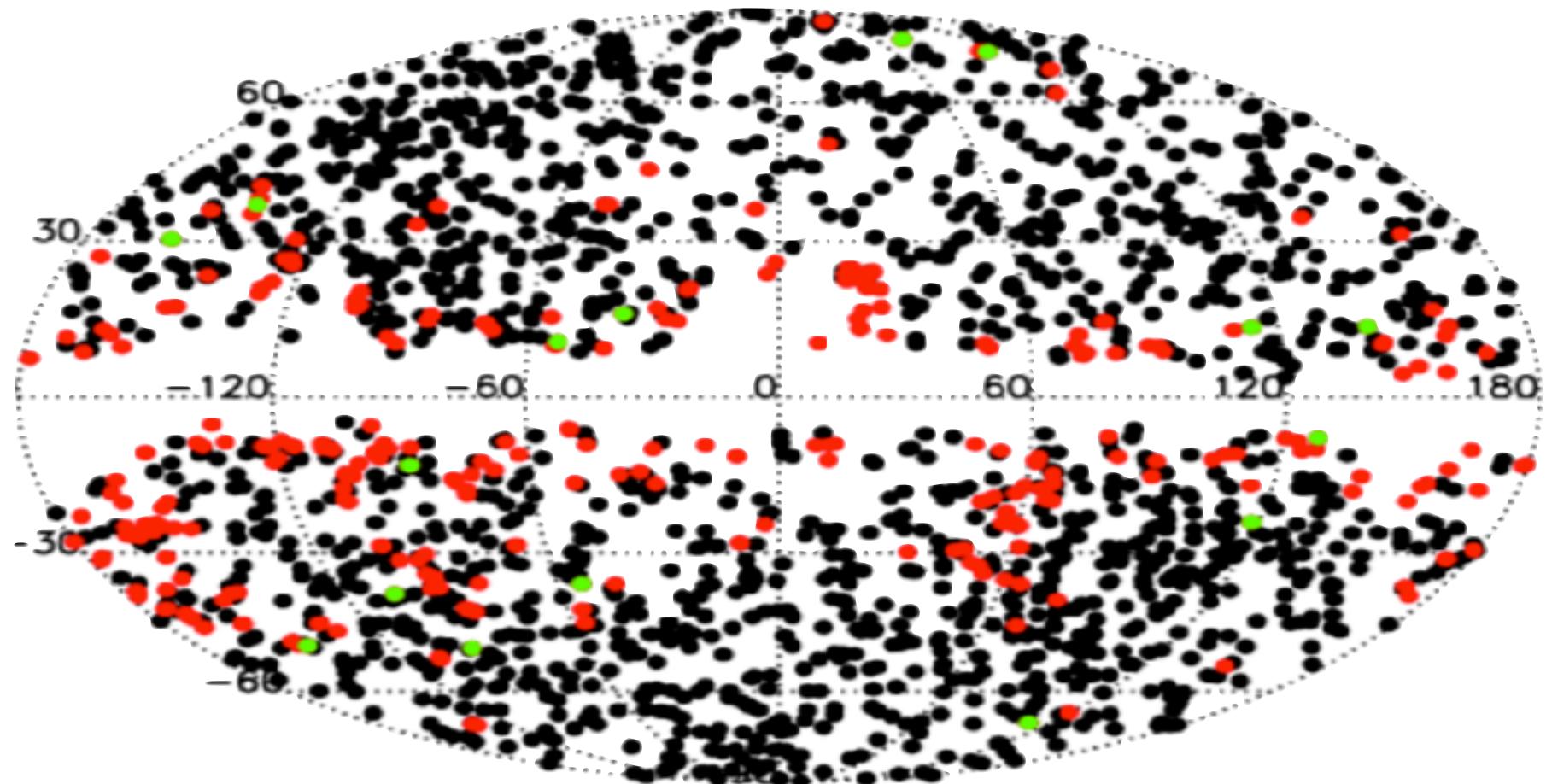


# **Beyond the $y$ -map Power Spectrum: Mocking Cluster Selection & Masking**

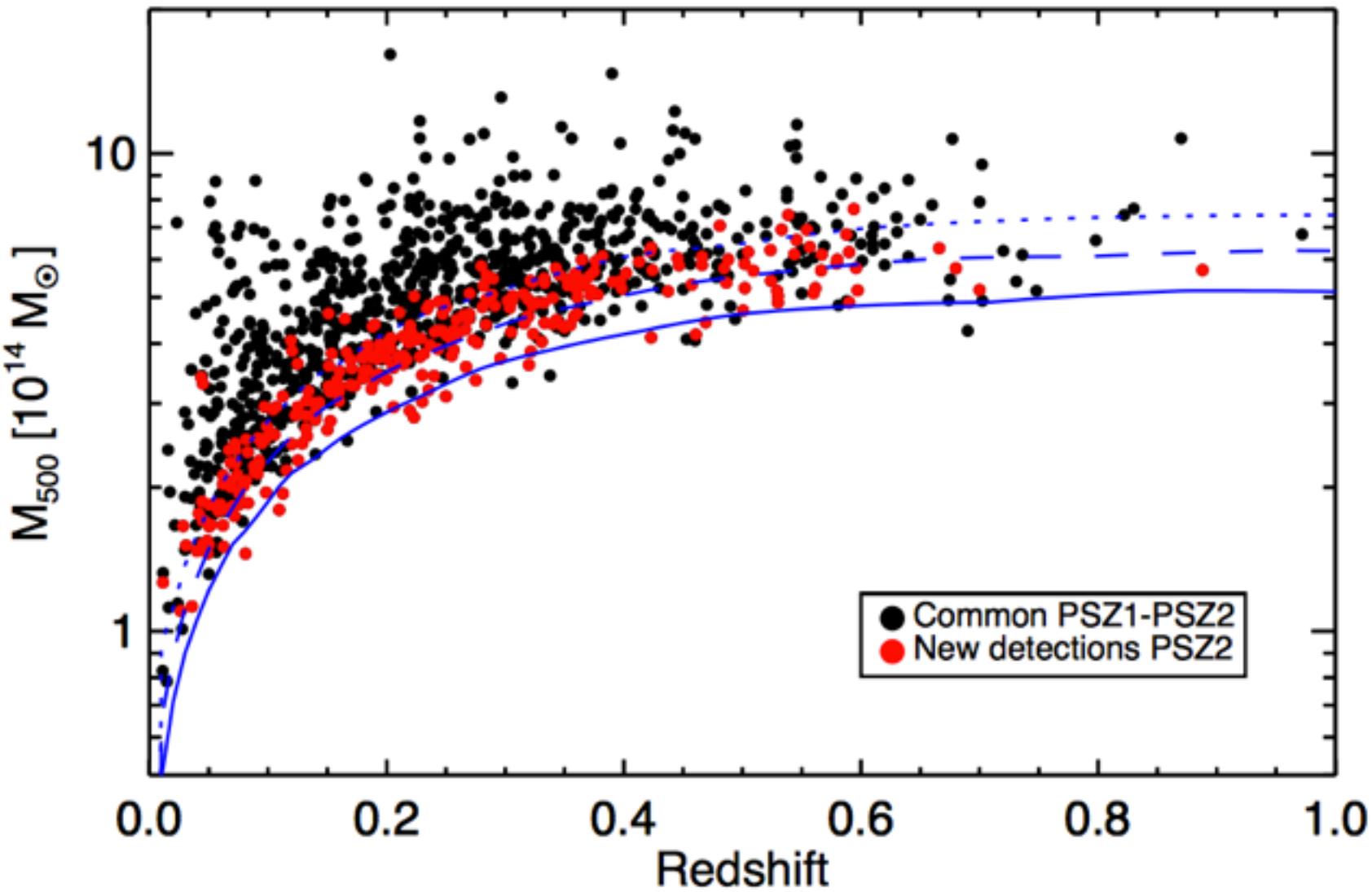
Separating and cross-correlating  
**nearly-Gaussian (2-halo)**  
and  
**highly non-Gaussian (1-halo)**  
in *same  $y$ -map*



# Planck Catalog of SZ Sources



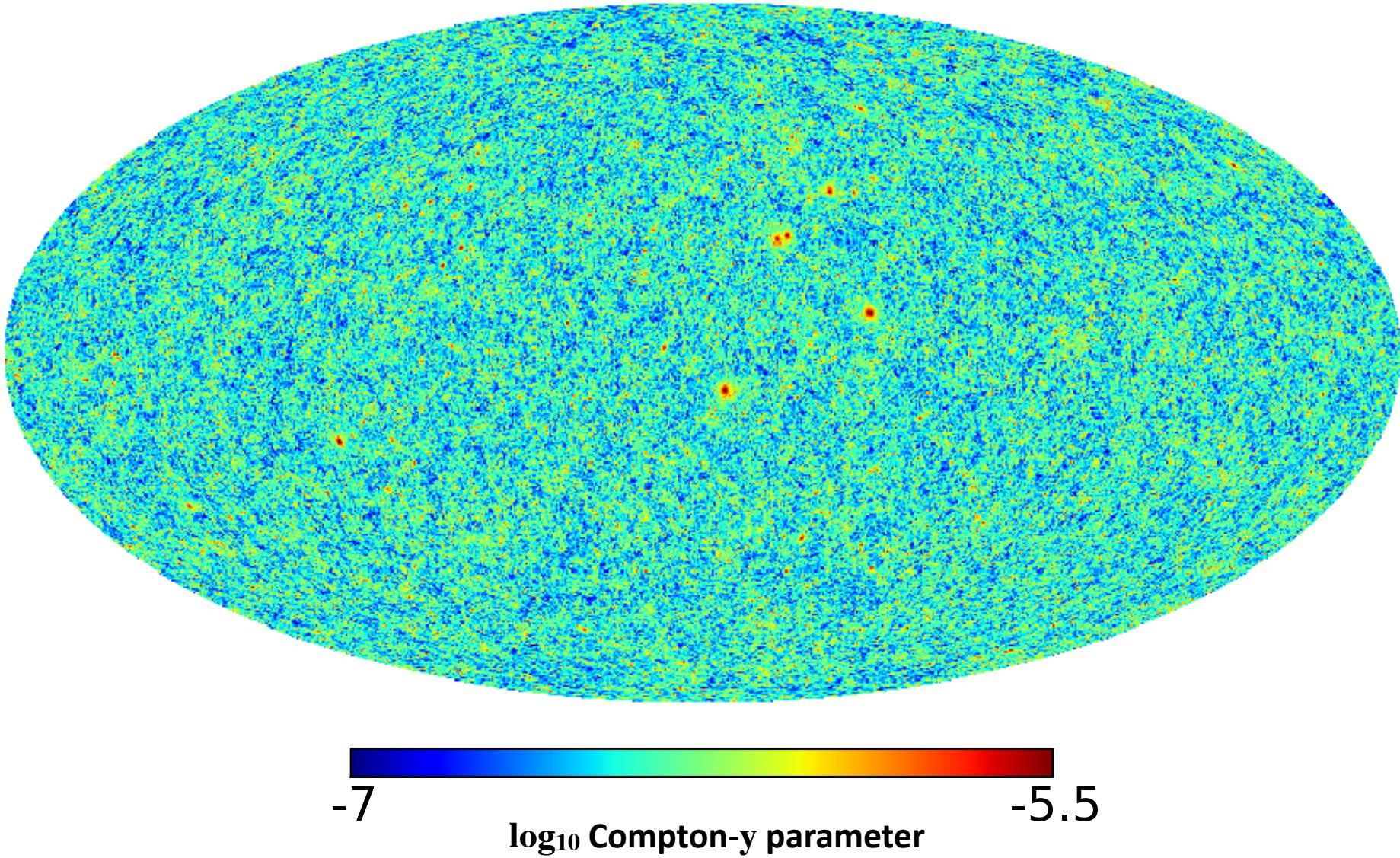
# Planck Cluster Selection Function



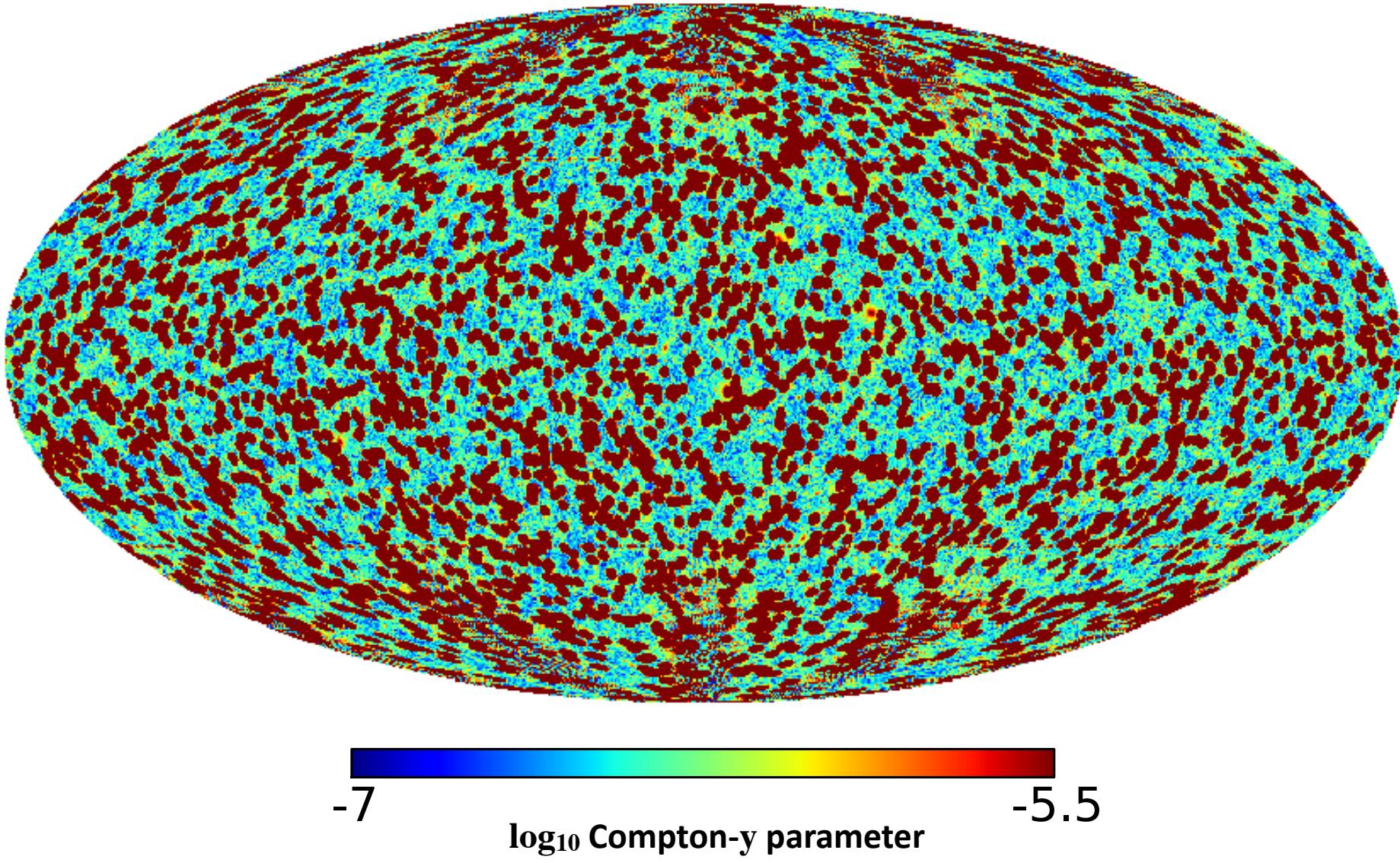
What Happens if we Correlate  
***Detected Clusters***  
with  
***The Rest of the Map?***



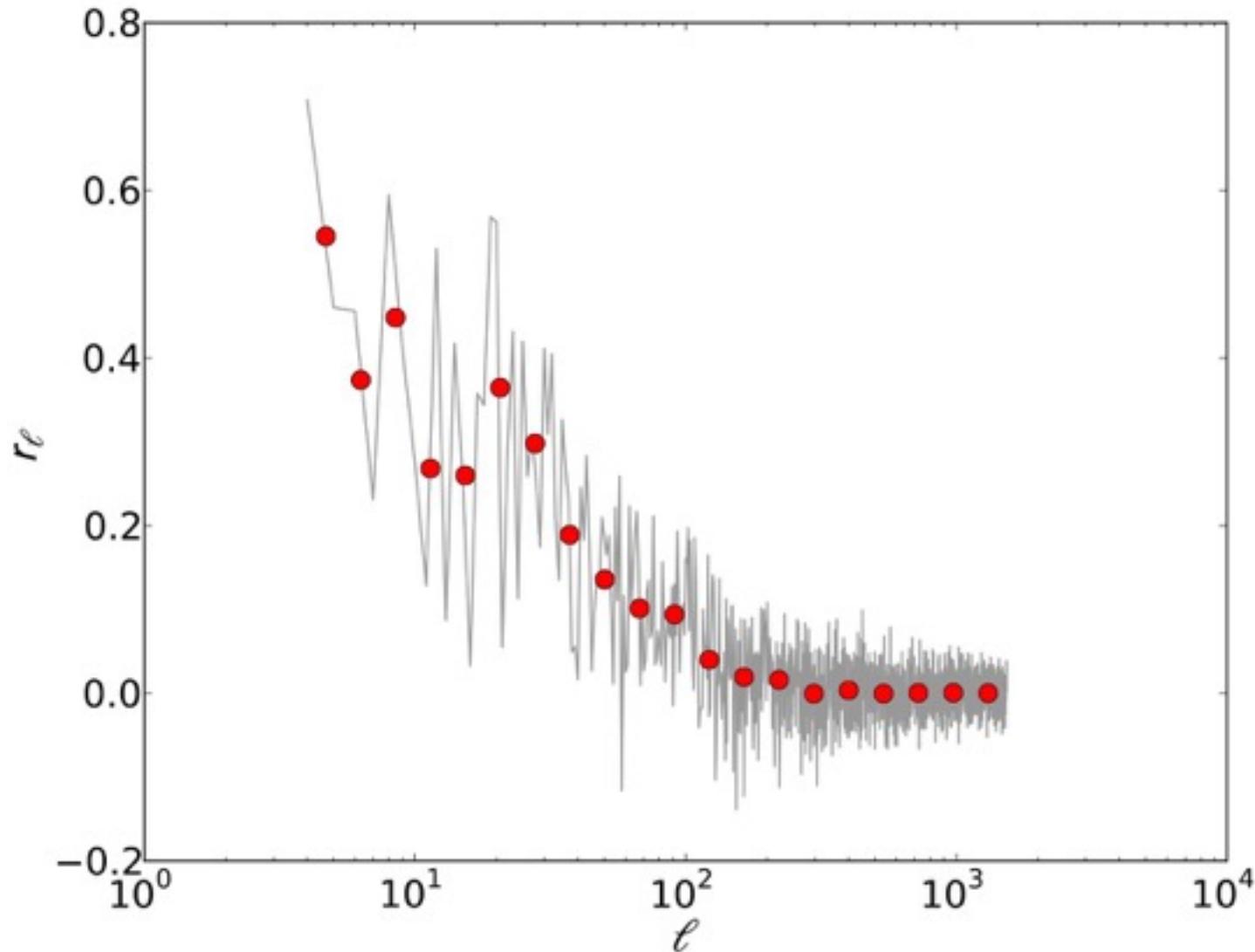
# Map with Selected Clusters Removed



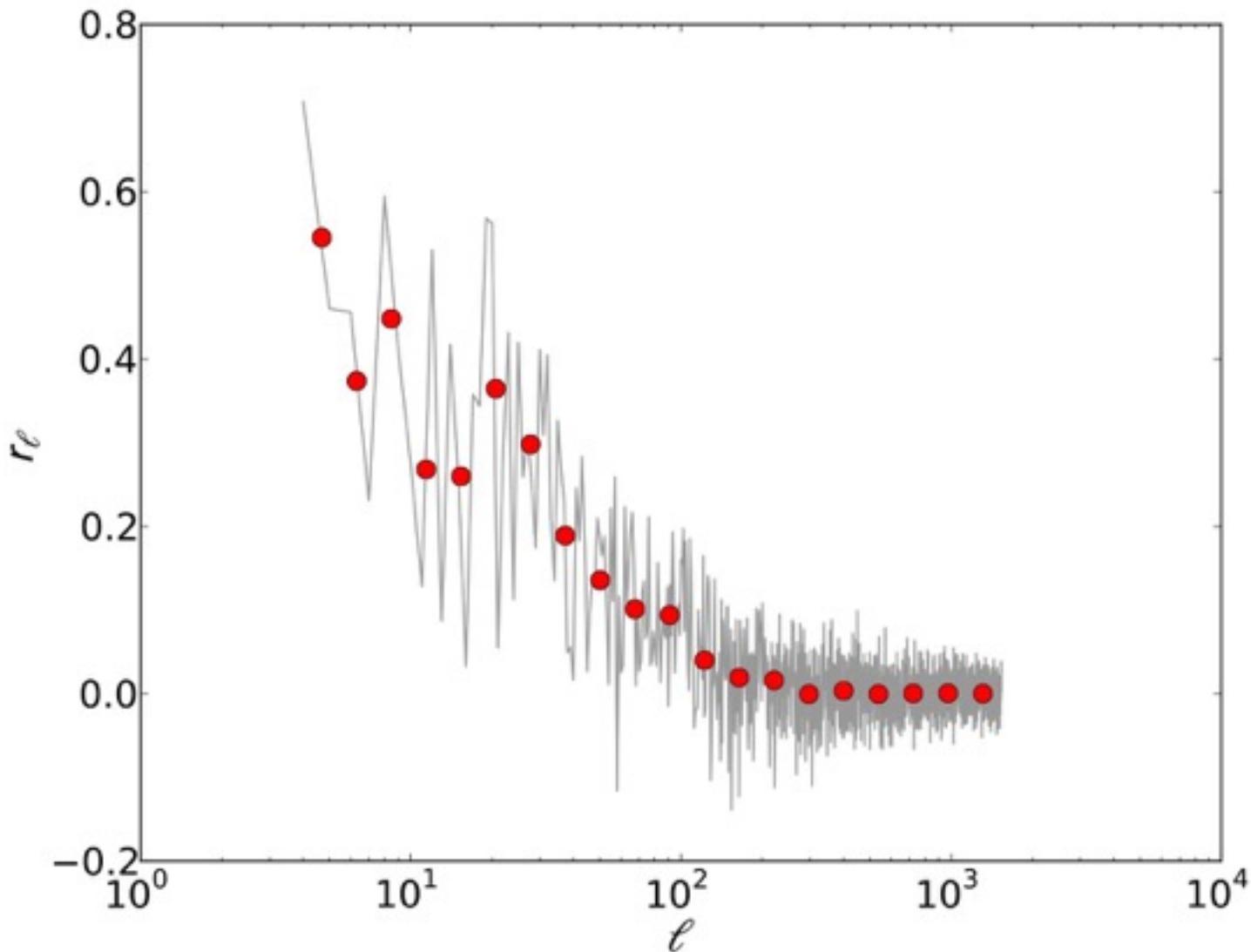
# Location of Selected Clusters



# Cross-correlation of *PSZ2 selected-clusters* with Compton $y$ -map for Single Map chosen at Random



# Redshift Information is Lost but Cross-correlation Survives for $\ell < 200$



# Using Redshift Information to Convert Angle to Distance

## Clustering of Clusters & Groups

$PSZ(redshift)$   
x  
*(PSZ masked) Planck y-map*

$$p_{yc}(k) = \sum_i r_{\ell=k\chi_i}^2 c_{\ell=k\chi_i}^{yc,i} / \sum_i r_{\ell=k\chi_i}^2$$



# Using Redshift Information to Convert Angle to Distance

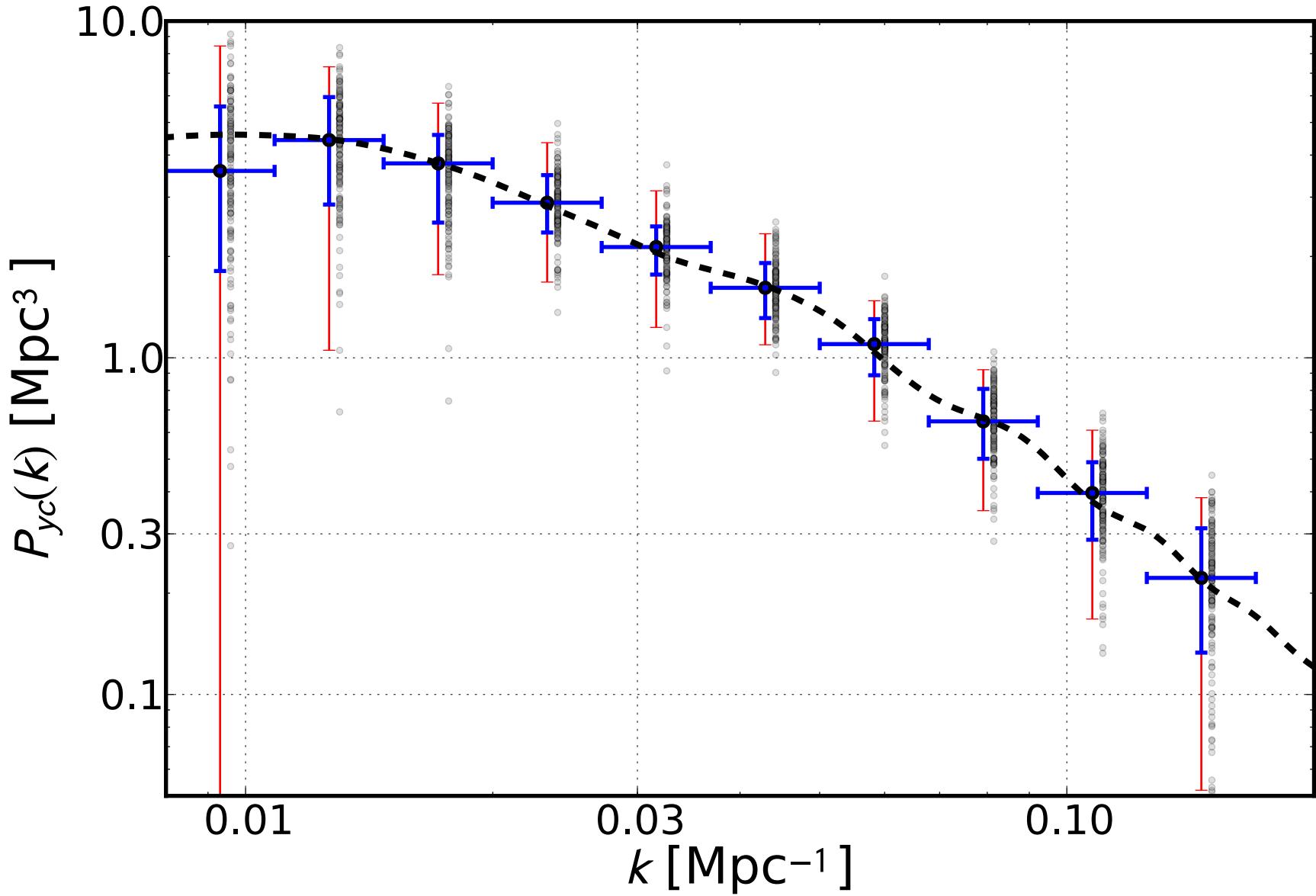
## Clustering of Clusters & Groups

$PSZ(redshift)$   
x  
*(PSZ masked) Planck y-map*

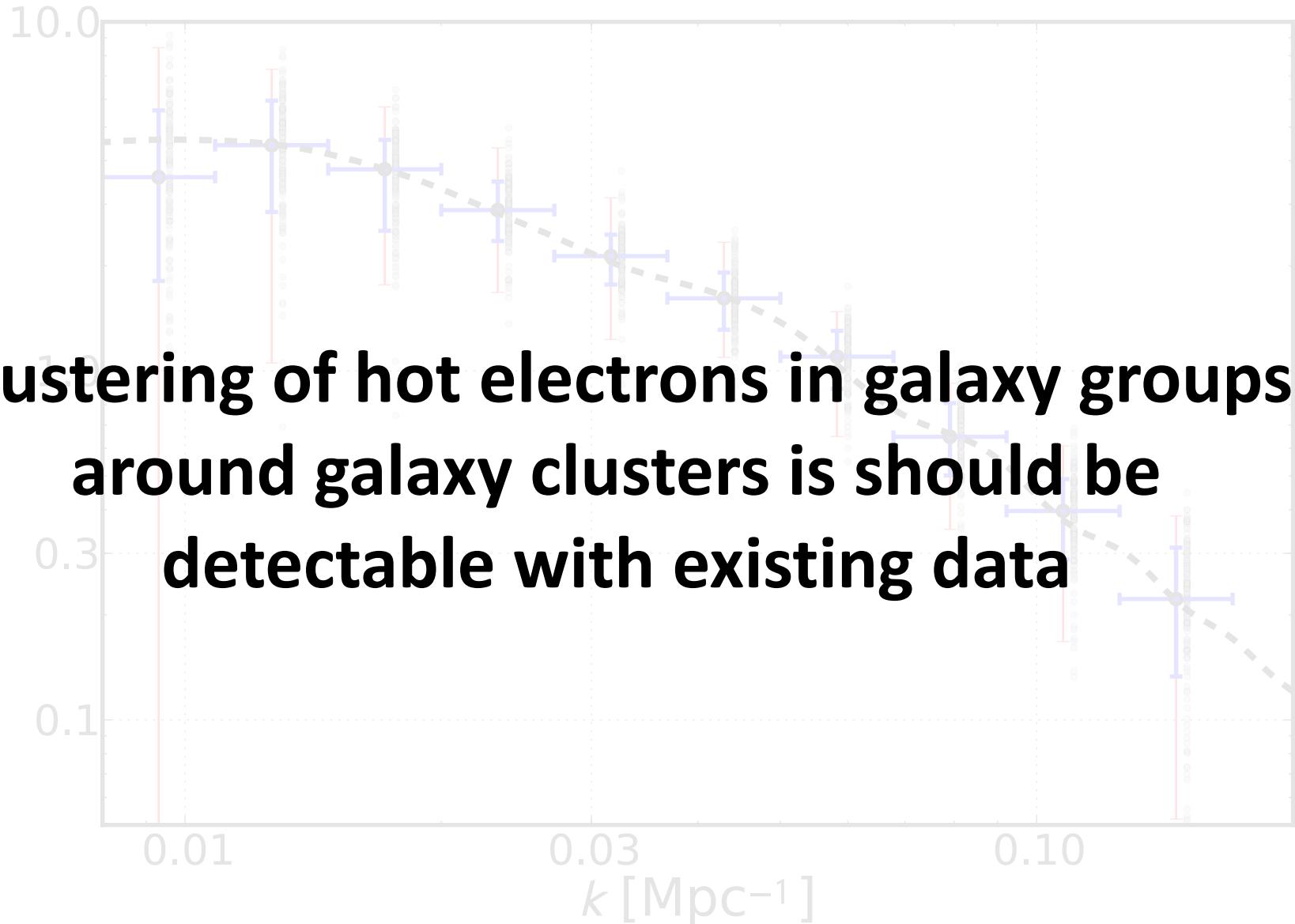
$$p_{yc}(k) = \sum_i r_{\ell=k\chi_i}^2 c_{\ell=k\chi_i}^{yc,i} / \sum_i r_{\ell=k\chi_i}^2$$

Redshift bins





$$P_{yc}(k) [\mathrm{Mpc}^3]$$



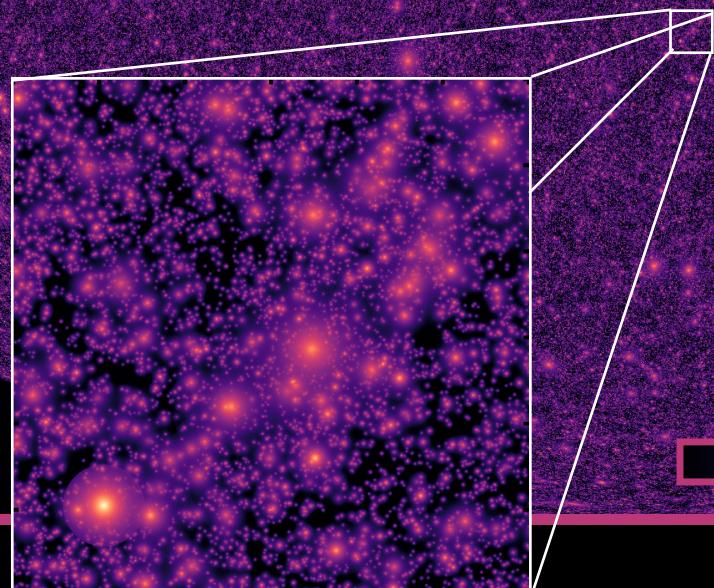
# Current Full Sky Model



# Battaglia et al. (2012) fits for Pressure Profiles

$0.00 < z < 1.25$   
 $8\text{Gpc}, 4096^3 \text{ Box}$   
 $N = 6.5 \times 10^6$

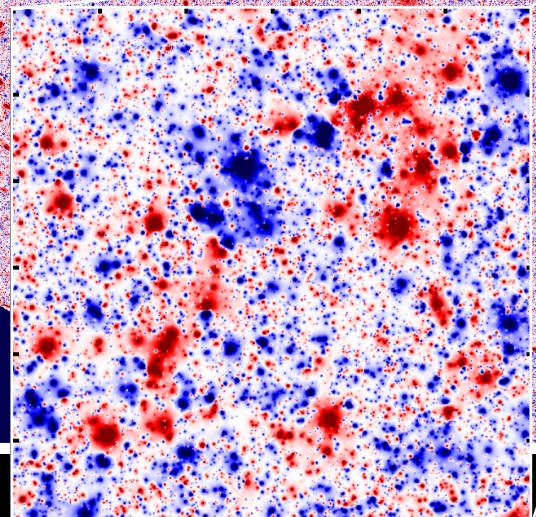
tSZ



## Battaglia et al. (2012) fits for Gas Density Profiles

$0.00 < z < 1.25$   
 $8\text{Gpc}, 4096^3 \text{ Box}$   
 $N = 6.5 \times 10^6$

kSZ

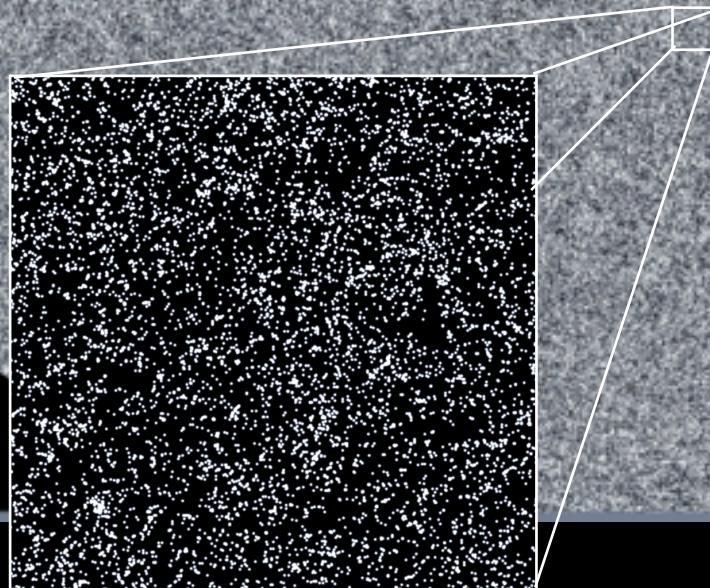


6 deg



$0.00 < z < 1.25$   
 $8\text{Gpc}, 4096^3 \text{ Box}$   
 $N = 9.9 \times 10^6$

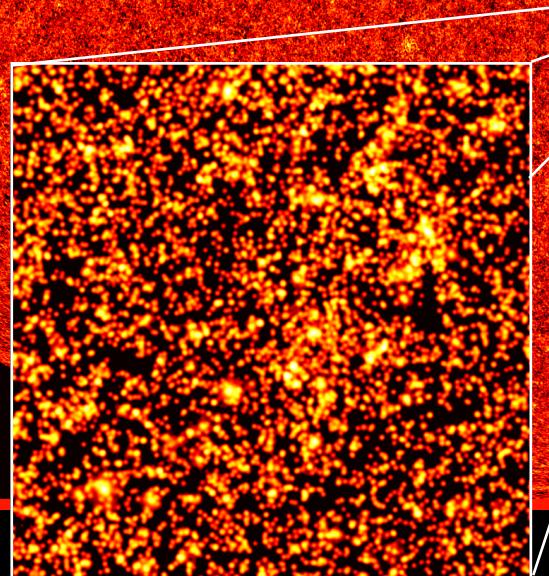
Optical



Shang et al. (2012) DSFG HOD + Dust SED Model

$0.00 < z < 1.25$   
 $8\text{Gpc}, 4096^3 \text{ Box}$   
 $N = 232 \times 10^6$

CIB



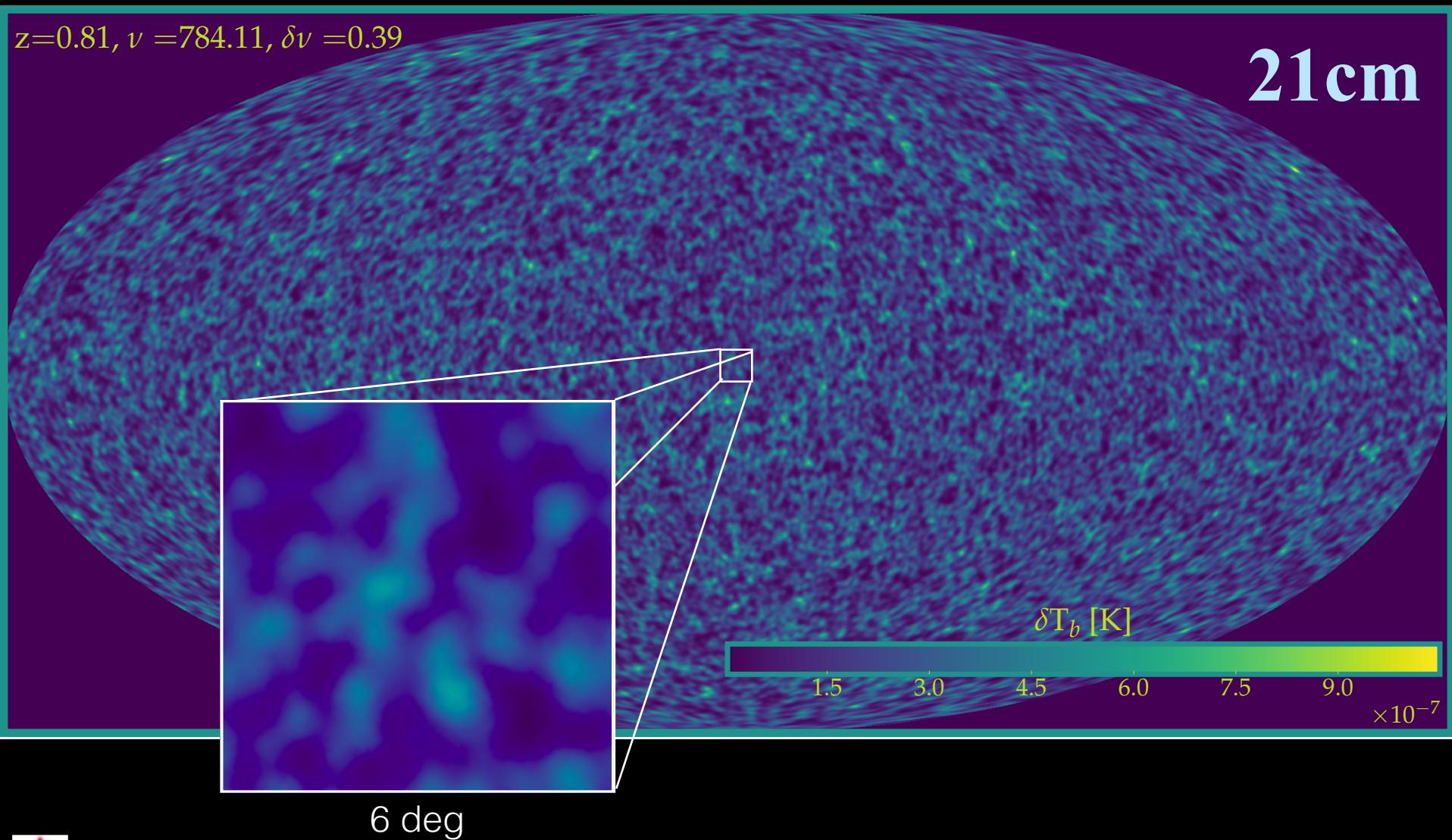
6 deg

log MJy/sr

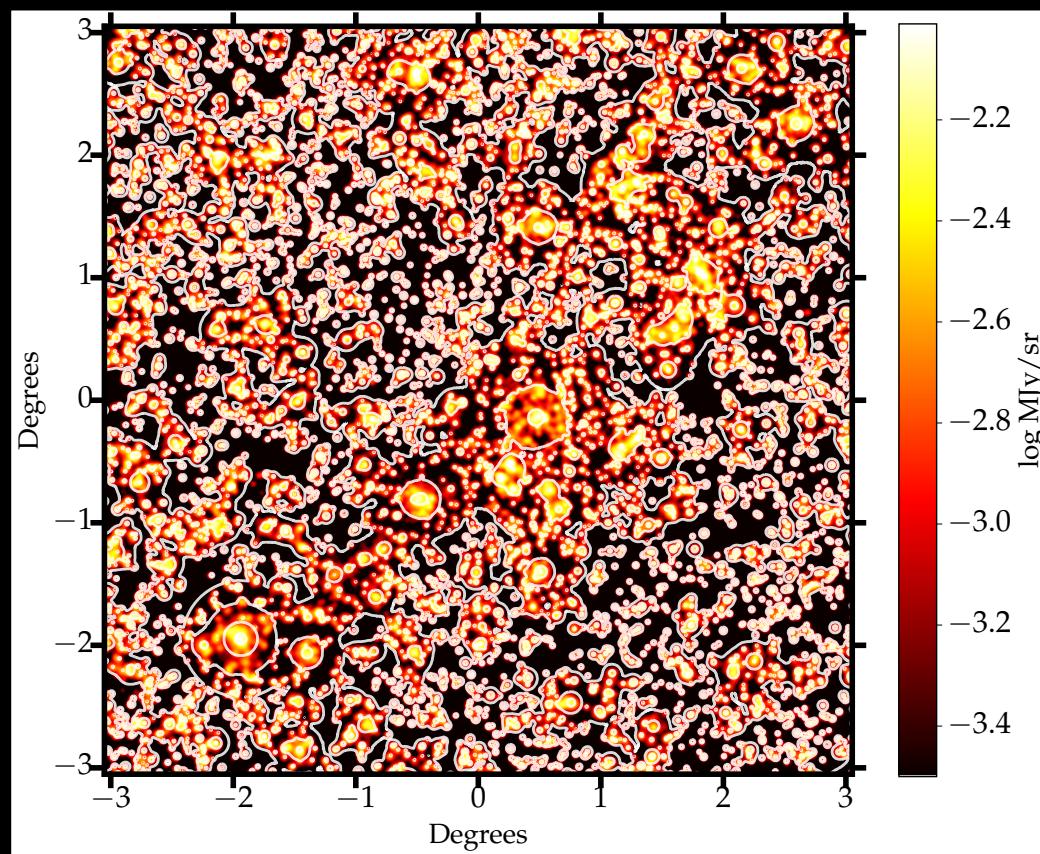
-3.4 -3.2 -3.0 -2.8 -2.6 -2.4 -2.2



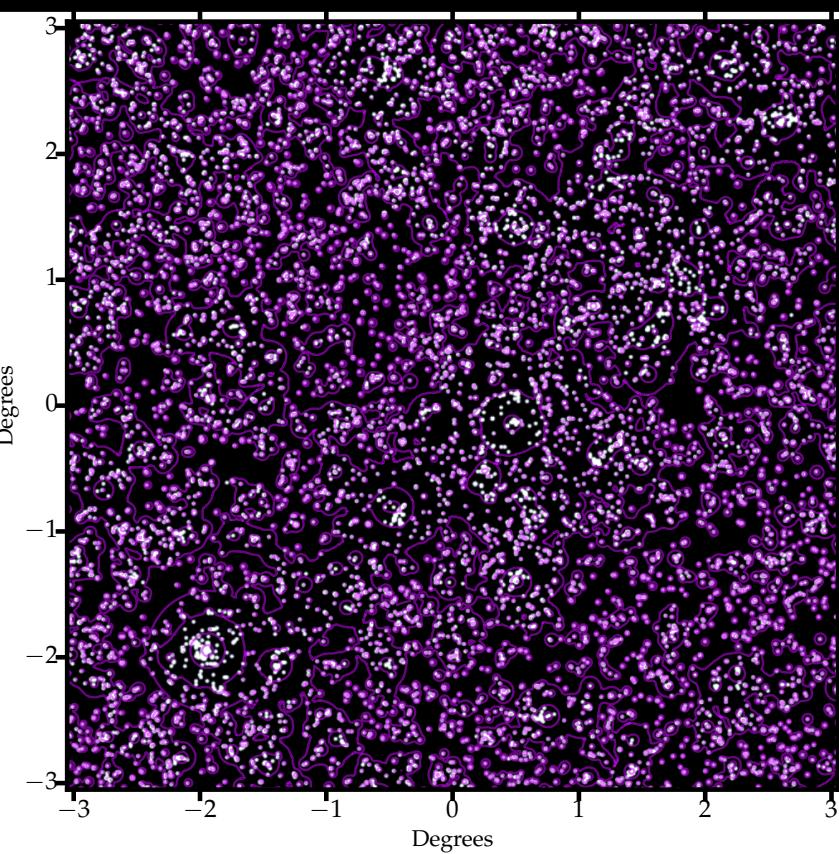
Berger et al. Subgrid +  $M_{\text{HI}}(M_{\text{halo}})$  Model



# CIB x tSZ



# Optical x tSZ



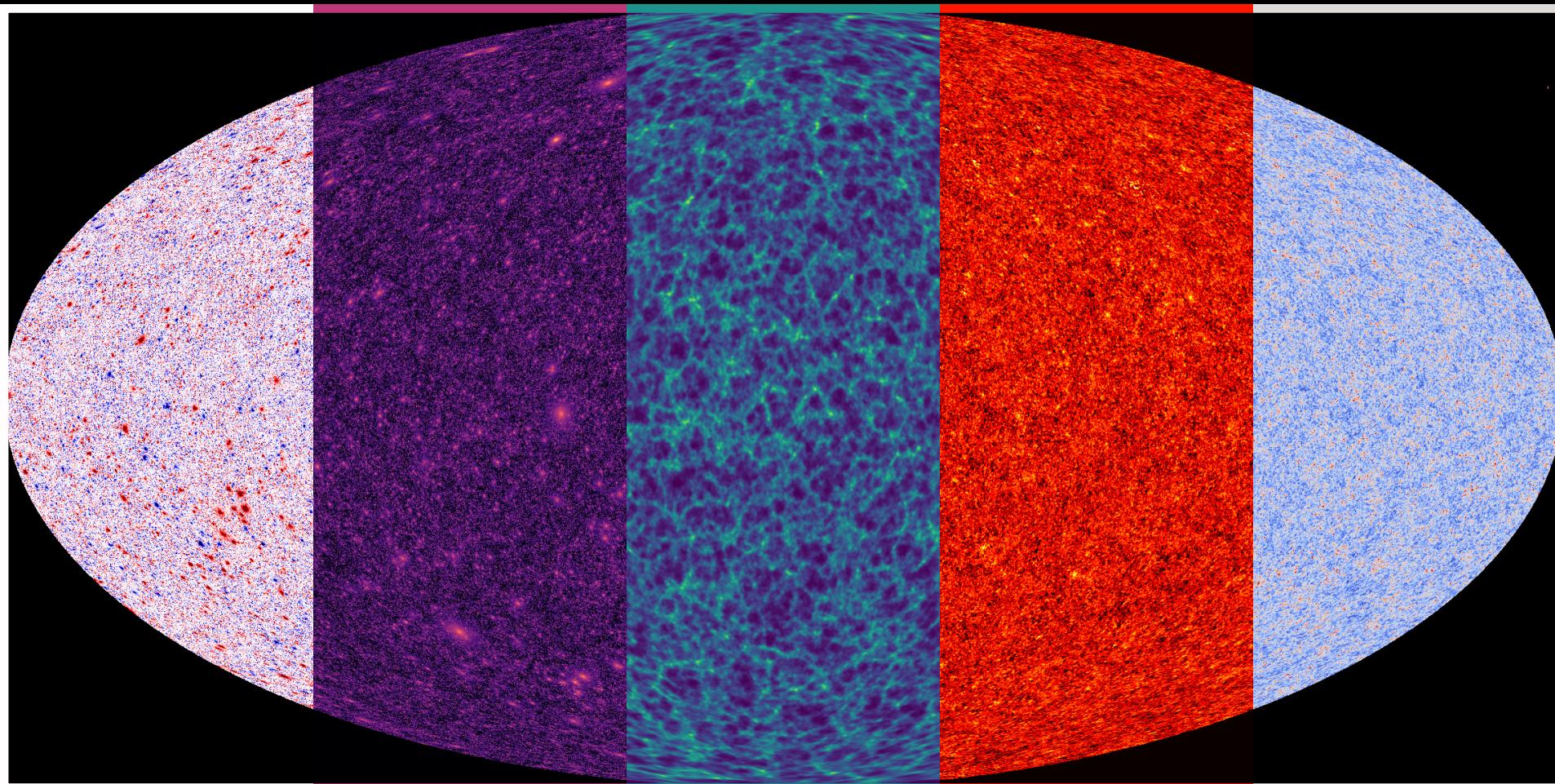
kSZ

tSZ

HI

CIB

Optical

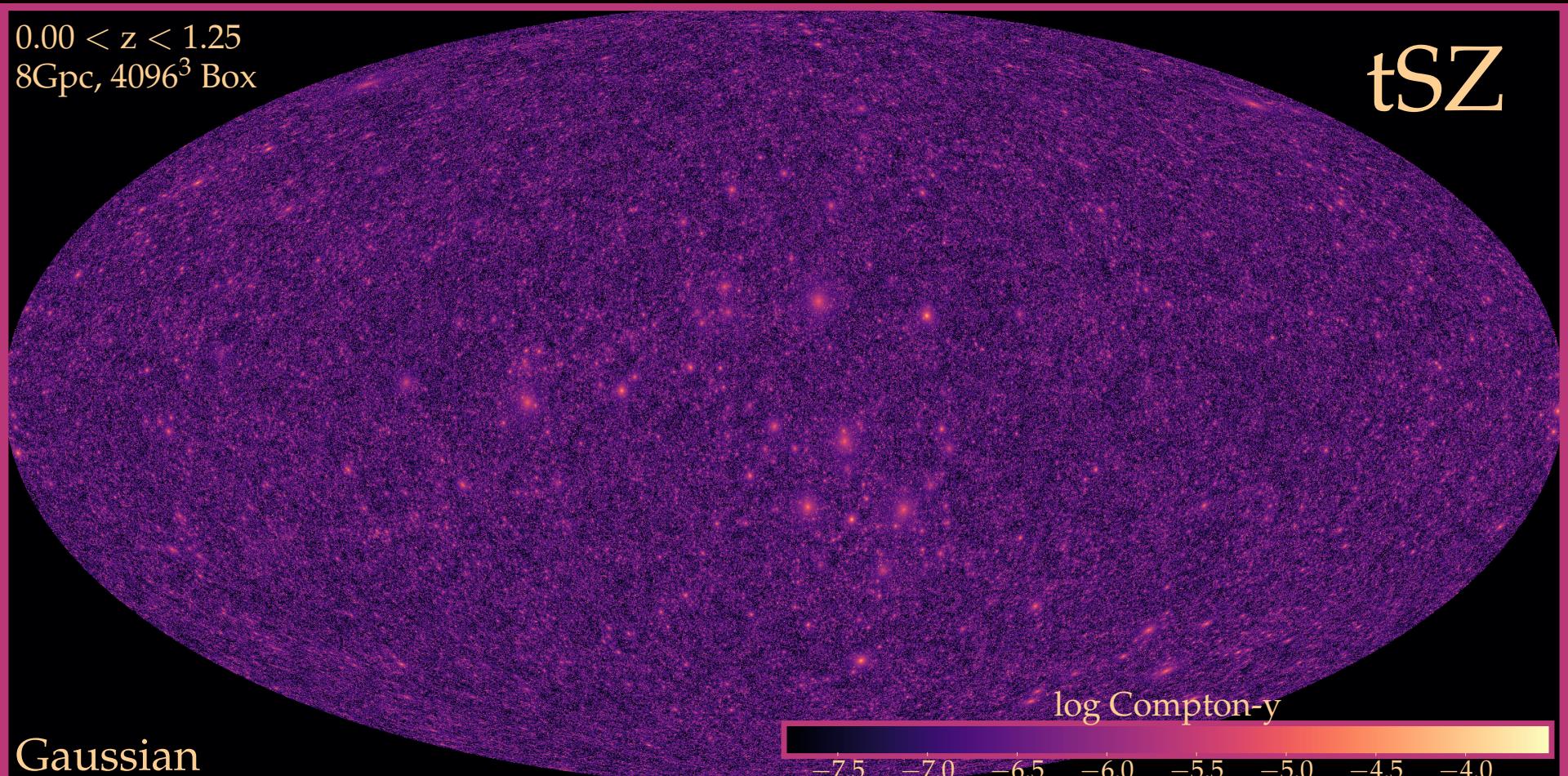


# **Exploring non-Perturbative (intermittent) non-Gaussianity**



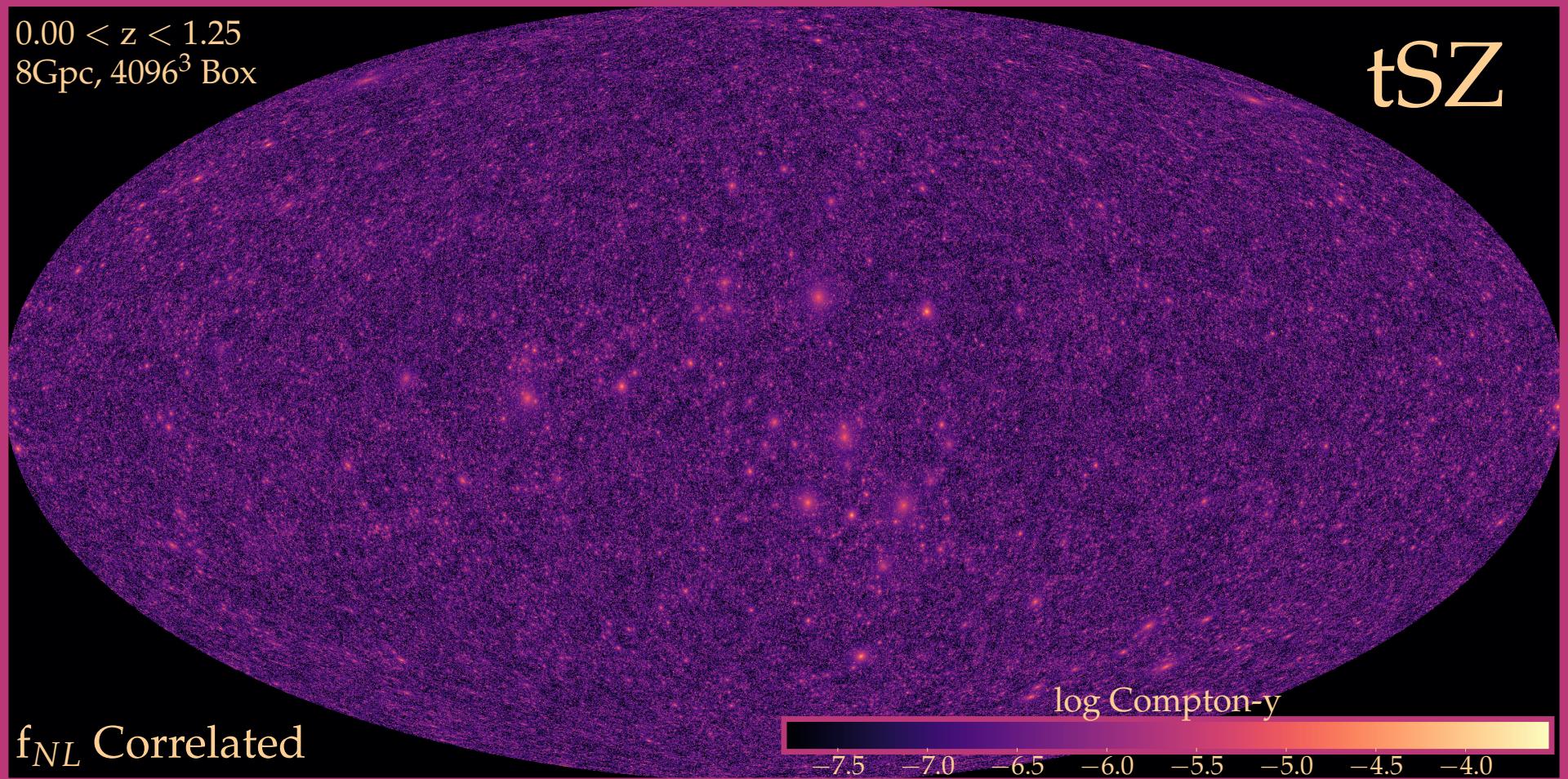
$0.00 < z < 1.25$   
8Gpc,  $4096^3$  Box

tSZ



$0.00 < z < 1.25$   
8Gpc,  $4096^3$  Box

tSZ



$0.00 < z < 1.25$   
8Gpc,  $4096^3$  Box

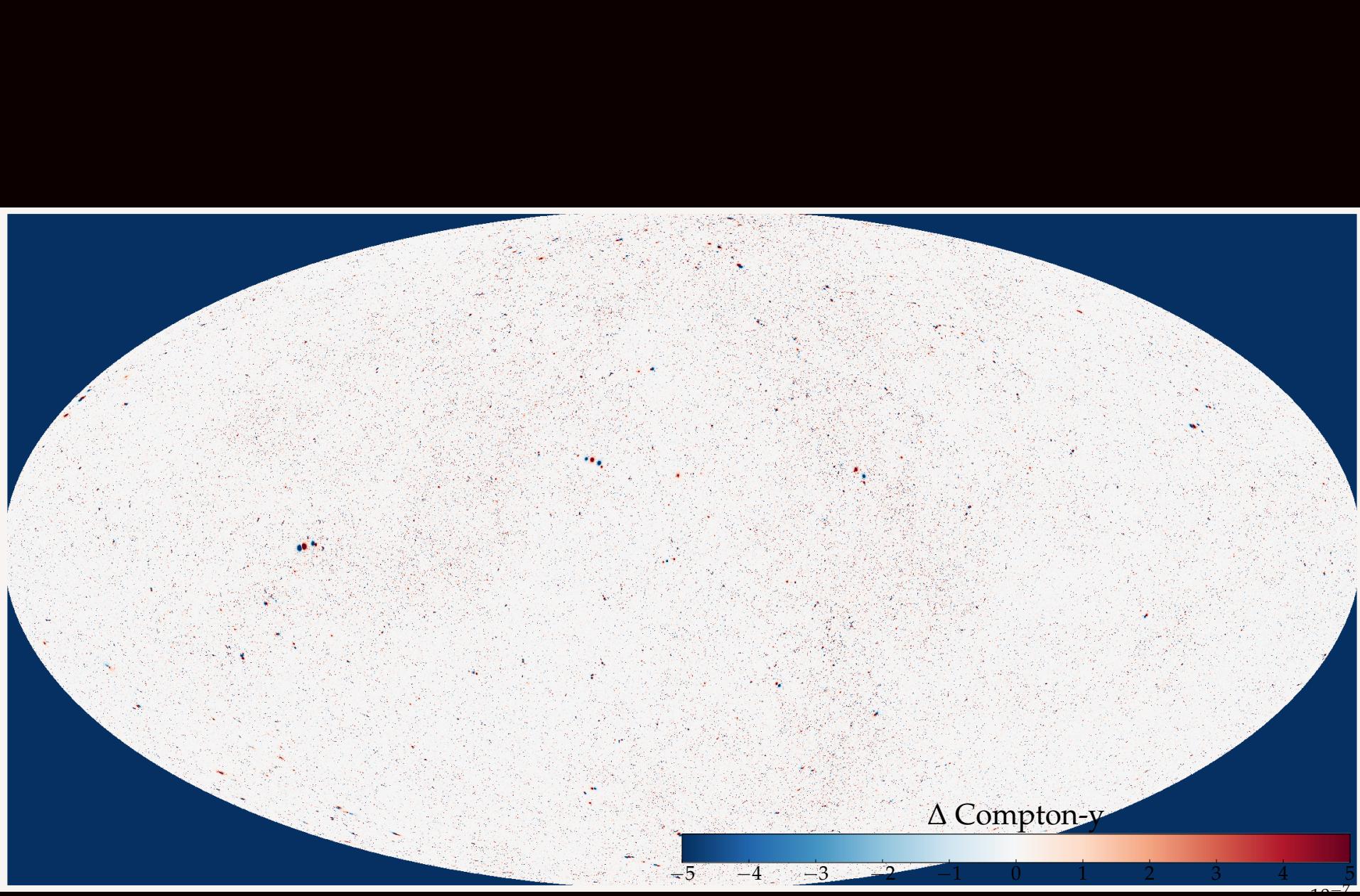
tSZ

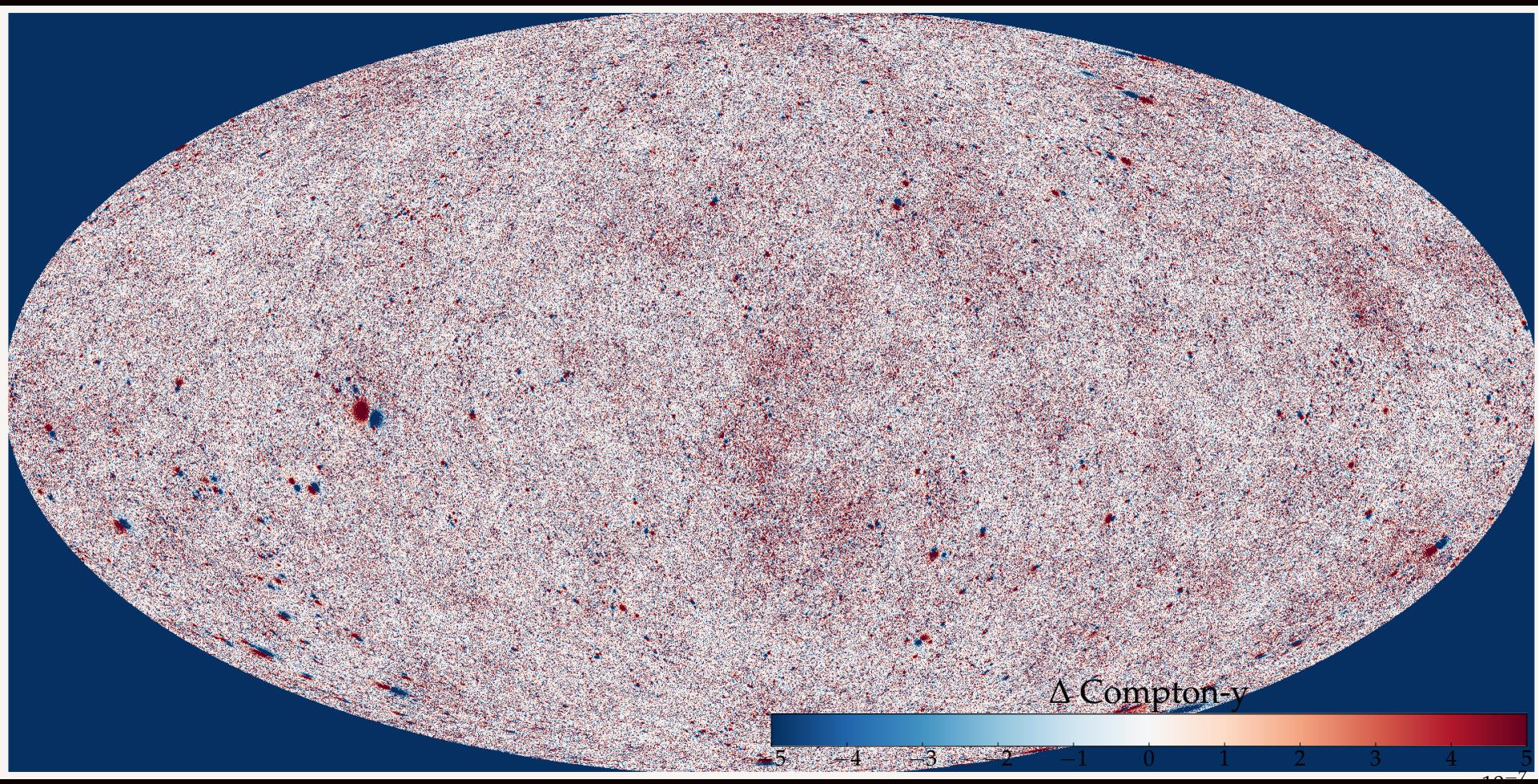
Spike

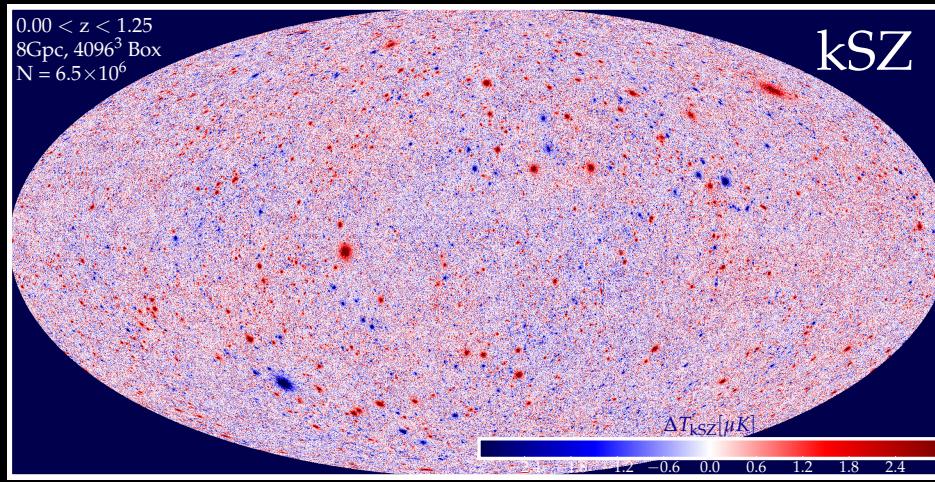
log Compton-y

-7.5 -7.0 -6.5 -6.0 -5.5 -5.0 -4.5 -4.0





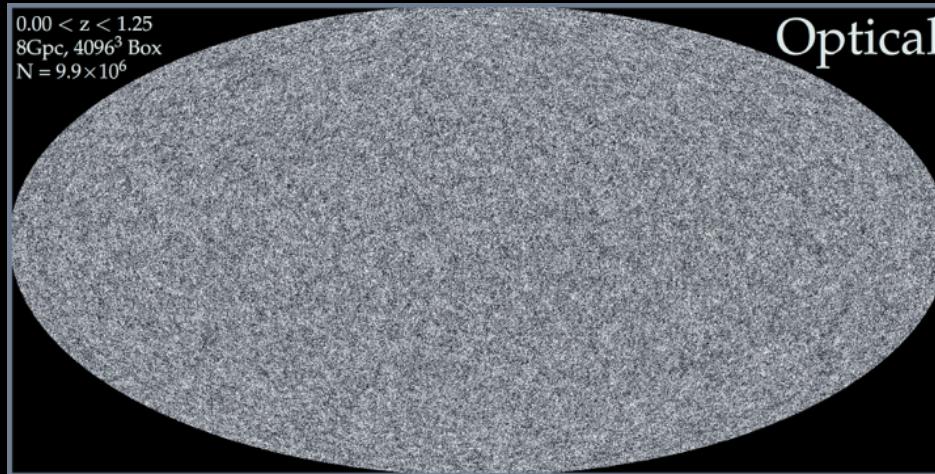




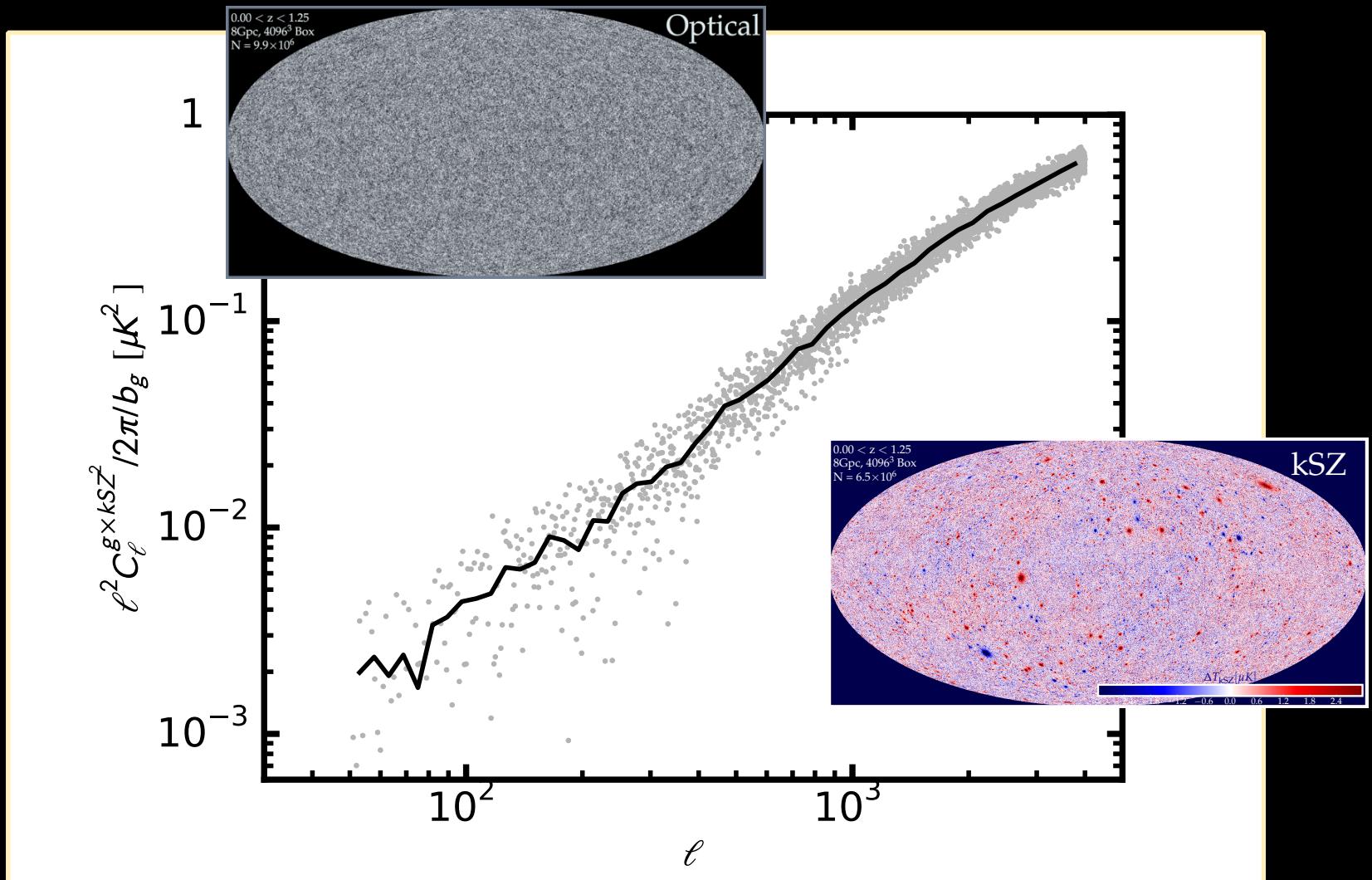
$(T_{\text{kSZ}})^2$

x

Full Sky CMASS HOD



# $(T_{\text{ksz}})^2 \times \text{CMASS HOD}$ (Preliminary)



# Summary

New cosmological surveys require simulations with fast, accurate, and high dynamic ranges

Our parallel implementation of ellipsoidal peak dynamics reproduces N-body halo masses and positions **~1000 times faster** and allows efficient exploration of cosmological theory space

Monte Carlo all-sky realizations of tSZ maps and shows that Clustering of Galaxies is easily detectable with current data

## Future Directions

Mocks Tailored to Individual Surveys & their Cross-correlations:  
Optical, CMB, X-ray, and Hydrogen and CO/C Intensity Mapping

Statistics to formalize “what is an LSS anomaly?”

Non-Gaussianity (perturbative and not) & Modified Gravity

Much improved dynamics over (1/2)LPT

Bug us to Collaborate on Mocks!

